Analysis on Modulation Techniques of an AC drive with Respect to Harmonic Content and Efficiency

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Abstract: **Inverters have become popularly used in the field of Power Electronics for different applications. The presence of harmonics in the output voltage of the inverters have led to many research works being conducted. Different topologies were applied to mitigate this inverter drawback, thus improving the efficiency of the inverter. SPWM, HCCPWM and MSPWM techniques have been discussed and implemented in Matlab/Simulink software. Full-bridge single phase topology is used. Simulations results are presented. The common parameters between the three techniques are modulation index and the number of pulses. Minimum Total Harmonic Distortion (THD) is used as a criterion key performance indicator (KPI) in comparing the output results generated from all the techniques investigated and verified. The results show that Modified Sinusoidal PWM technique produce better results as compared to SPWM and HCCPWM techniques. The results generated from MSPWM technique have reduced harmonics and the output voltage is more sinusoidal without the use of an ideal switching method. This paper demonstrated the output voltage performance comparison between SPWM, HCC and MSPWM implemented in the unipolar inverter.**

Keywords—Sinusoidal Pulse Width (SPWM), Hysteresis-band Current Control (HCC), Space Vector Pulse Width (SVPWM), Selective Harmonic Elimination (SHE), and Phase Shifted Carrier PWM (PSCPWM).

I. INTRODUCTION

In the recent years, multiphase voltage source inverter (VSI) have been widely utilized for multi-phase induction motor for variable frequency and variable voltage. Applications such as locomotive traction, electric aircraft, electric ship propulsion, electric and hybrid electric vehicles and other high-power electronics. VSI is a step-down type of an inverter and use PWM techniques. Current Source Inverter (CSI) is not mostly used due to commutation complexity in the circuit. Innovative techniques have been developed to overcome the poor utilization of input DC voltage. It has been observed that the pattern of Pulse Width Modulation (PWM) can enhance a fundamental component in an intelligent manner. Widened width of pulse at the middle of the waveform leads to an enhanced fundamental output voltage and reduced harmonic contents [5, 7 & 8]. In the literature, the harmonic content reduction in the output voltage and current waveforms of the converters has been researched in the past years [6]. Inverter output waveforms (either voltage or current) are usually rectilinear in nature and contains harmonics which may lead to reduced load efficiency and performance [2]. A.C. drives are called Inverters and are mostly used for industrial applications for speed control of a motor mechanism. Different modulation techniques are used to eliminate harmonics in A.C. drives. These modulation techniques have different algorithms. The

purpose of any modulation technique is to obtain variable output having a maximum fundamental component with minimum harmonics [9 &10]. To control the switching pattern of the inverter different PWM techniques are applied such as; Sinusoidal Pulse Width (SPWM), Space Vector PWM (SVPWM), Selective Harmonic Elimination (SHE), Hysteresis Band Current Control (HCC PWM), Trapezoidal Pulse Width Modulation Technique (TPWM), Third Harmonic Injection Pulse Width Modulation (THIPWM). This paper will only focus on SPWM, HCC and Modified SPWM and results will be analyzed.

II. MODULATION TECHNIQUES

A. Sinusoidal PWM technique

Sinusoidal Pulse Width Modulation Technique is widely used in Power Electronics. SPWM has been mostly used in power converters owing to its simplicity to generate good output waveform with tightly controlled harmonic contents. The main drawback of SPWM is harmonic amplitudes of the energy associated with the switching frequency and multipliers are very high [1, 3, 8, 10, 13, 14 & 15]. The main advantage of carrier-based SPWM is very low complexity and the dynamic response is good for matrix converters [16]. SPWM has two classifications such as: Bipolar and Unipolar techniques. In Bipolar SPWM technique sine wave gets compared with the triangular wave and based on the comparison, gating signals are generated. Another method is Unipolar SPWM, this method has two sinusoidal waveforms with given offset that are compared with a triangular waveform and based on comparison the gating signals are generated for internal control of the inverter [1, 4, 10 & 12]. The SPWM can provide gate triggering signal for controlling the IGBT or MOSFET switches in power converters. The important parameter needed to design SPWM is the modulation index "m". By varying this parameter, the amplitude of the output voltage can be changed. SPWM gate pulses can be created as shown in Figure 1:
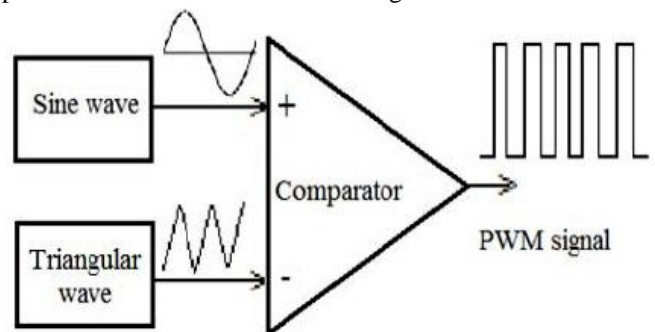

Figure 1: PWM signal generating [24].

The output frequency of the inverter can be determined by the reference signal frequency. The reference signal frequency can be applied to the carrier frequency as well as to identify the number of pulses per half cycle.

$$n_p = \frac{f_c}{f_r} \qquad (1)$$

Where, n_p is the number of pulses per half cycle. The ratio between the amplitude of the reference voltage V_r to the amplitude of the carrier voltage signal V_c gives the modulation index as defined below:

$$m = \frac{V_r}{V_c} \qquad (2)$$

With PWM designed with proper m, one can get an output voltage waveform with minimum THD [23]. SPWM in this case is operated by Unipolar inverter switching scheme. The two reference signals phase shifted by 180º have the same magnitude and frequency and are compared with high frequency rectangular signal and is used to generate Sinusoidal PWM [24]. Inverters that use PWM switching techniques have DC input voltage that is usually constant in size [25].

B. Hysteresis –Band Current Control Pulse Width Modulation (HCCPWM)

Hysteresis-band Current Controller is a popular PWM technique because of its implementation simplicity, fast transient response, direct limiting of device peak current. HCC PWM control method usually requires voltage and current sensors for successful implementation in almost all conditions including unbalanced conditions. The HCC is basically an instantaneous feedback current control method of PWM where the actual current continually tracks the command current within a hysteresis band [11&19-21]. The aim of HCC is to keep outside current of the converter within hysteresis band determined. The advantages of this technique are simple control algorithm, Dynamic response, good accuracy, robustness and robustness, simple in design and there is no need for information about load parameters required [15, 17 & 18].
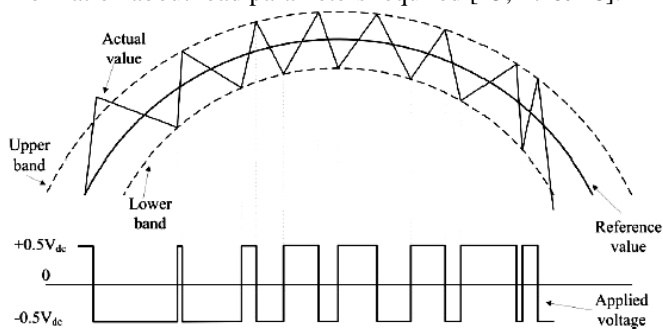
Figure 2: Principle of Hysteresis Band Current Control [26].

The operation principle of Hysteresis Band Current Control for a half bridge inverter is shown in Figure 2. The control circuit generates the sine reference current wave. As the current

exceeds a prescribed hysteresis band, the upper switch in the half bridge is turned off and the lower switch is turned on. As a result, the output voltage transitions from $+0.5V_d$ to $-0.5V_d$, and then the current start to decay. As the current crosses the lower band limit, the lower switch is turned off and the upper switch is turned on. The actual current wave is thus forced to track the sine reference wave within the hysteresis band by back-and -forth switching of the upper and lower switches. The inverter then essentially becomes a current source with peak to peak current ripple, which is controlled within the hysteresis band irrespective of V_d fluctuation. The peak-to-peak current ripple and switching frequency is related to the width of the hysteresis band. The hysteresis current controller gives output pulses to the VSI inverter by applying the following algorithm: $|i_{m,ref} - i_m| < \varepsilon$ keeps the output pulse at the same state $|i_{m,ref} - i_m| > \varepsilon$ let output pulse = 1 (High) $|i_{m,ref} - i_m| < -\varepsilon$ let output pulse = 0 (Low) and where m = a,b,c phases and ε is the hysteresis band [26].

The equations or derivations of this scheme are:
$i_{ref}(t) = i_{m,ref} \sin(\omega t)$

Upper band $i_u = i_{m,ref(t)} + \Delta i \qquad (1)$

Lower band $i_l = i_{m,ref(t)} - \Delta i \qquad (2)$

Where Δi =hysteresis band limit

If $i_m > i_u$, $\qquad v_m = \frac{v_{dc}}{2}$

$\qquad (3)$

If $i_m < i_u$, $\qquad v_m = \frac{-v_{dc}}{2} \qquad (4)$

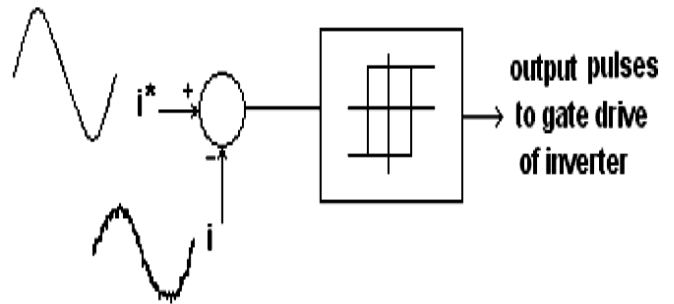i is load current and V_{dc} is the dc link voltage of the inverter.

Figure 3: Control block diagram of HBPWM [26].

Hysteresis comparators are used to force a hysteresis band from the reference current. Therefore, excellent dynamic performance is provided by this control scheme because of its quick action capability. The main disadvantage of this method is the PWM frequency not constant and non-optimum harmonics can be generated [26&27].

C. Modified Sinusoidal Pulse Width Modulation(MSPWM)

This is similar to traditional SPWM technique, where gating signals are generated by comparing sinusoidal reference signal with a triangular carrier wave and the width of each pulse is varied proportionally to the amplitude of a sine wave evaluated at the center of the same phase. When considering this MSPWM, the pulse width does not change significantly with the variation of modulation index. The reason is due to the characteristics of the sine wave. Hence the Sinusoidal PWM technique is modified so that the carrier signal can be applied during the first and last 60º intervals per half cycle as shown in Figure 4.
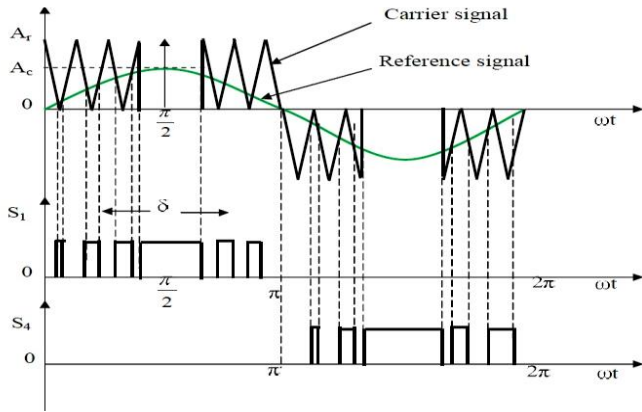

Figure 4: Generation of a Modified Sinusoidal Pulse Width [28, 31 &30].

When the fundamental component is increased the harmonic characteristics are improved. The main advantage of this technique is increased fundamental component, improved harmonic characteristics, reduced number of switching power devices and decreased switching losses. This technique was also proposed by Josias. W Makhubele, *et al* (2004) based Controller with modifications for controlling the output of the boost DC-A.C inverter as shown in figure 5.
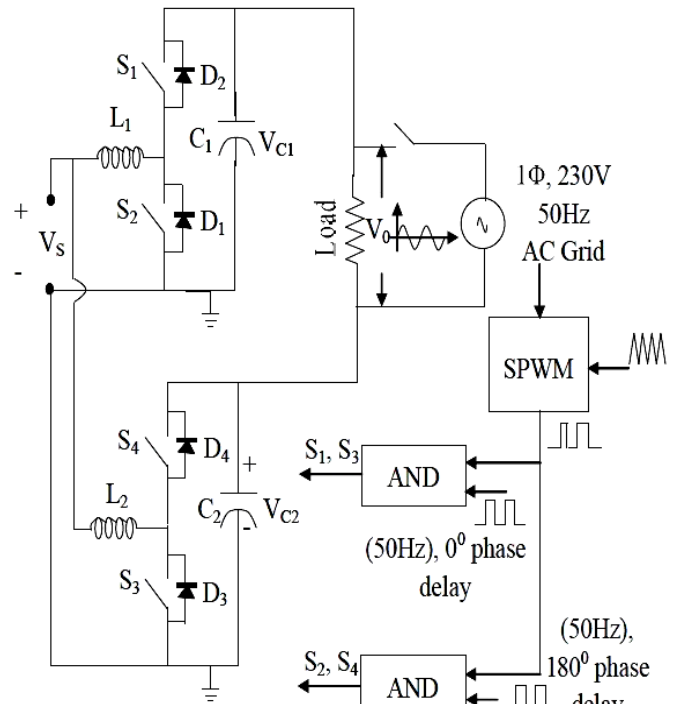

Figure 5: Circuit description of boost inverter with sinusoidal pulse width modulation technique based modified controller [31].

III. SIMULATION RESULTS

A. *Sinusoidal PWM technique*

Inverters that use PWM switching technique have a DC input voltage that is usually constant in magnitude. The inverter uses the frequency of the carrier or triangular as a switching frequency. This is usually kept constant. The carrier waveform V_c is at switching frequency F_c. This frequency controls the speed at which inverter switches are turned ON/OFF. The reference signal, V_{ref} is used to modulate the switch duty ratio, and has frequency F_r. This is the fundamental frequency of the inverter output. Since the output of the inverter is affected by switching frequency, it will contain harmonics at the switching frequency. So, the duty cycle of the inverter switches is called modulation ratio M_a.

In Bipolar SPWM technique, basic idea of comparing reference frequency signal with triangular or carrier signal to produce bipolar PWM switching signals is shown in Figure 6. When the instantaneous value of the sine reference is larger than the carrier the output is at $+V_{dc}$ and when the reference is less than the carrier, the output is at $-V_{dc}$ as shown in Figure 6.1 and figure 6.2 respectively [28].
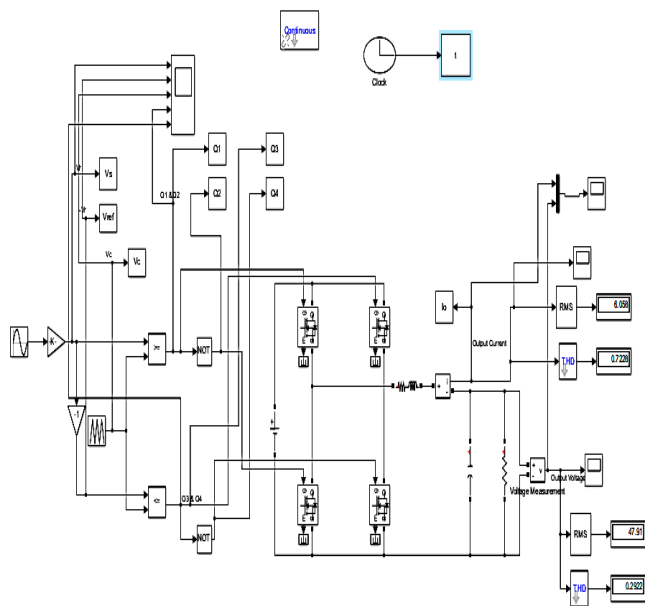
Figure 6: SPWM controller MATLAB Model.

As shown in Figure 6, the following are the parameters used in this model:

The line inductance and resistance are 1mH & 1mΩ, load resistance of 100Ω and capacitance of 1000µF, DC voltage of 100V at a switching frequency of 2kHz and fundamental frequency of 50Hz.
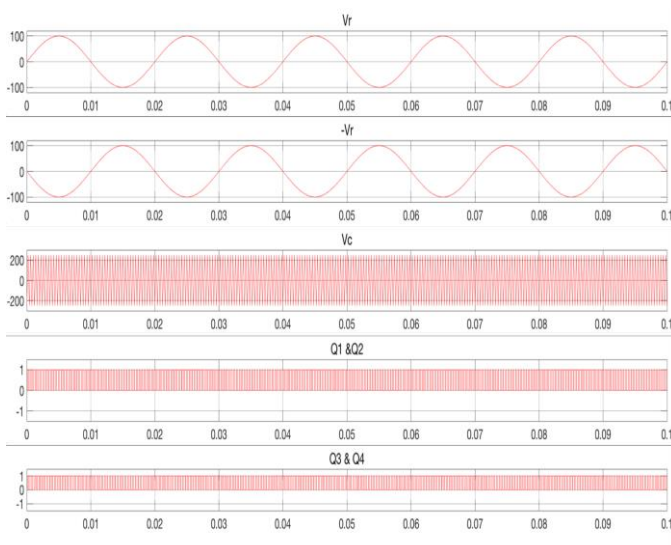

Figure 6.1: Simulated performance of Unipolar PWM inverter (fs=2kHz)

Unipolar SPWM switching scheme that is shown in Figure 6.1 was achieved by comparing two sinusoidal reference waveforms (Vr and -Vr) that have the same frequency and magnitude but are 180°phase shifted compared to triangular signal (Vc). The output generated by switches Q1 & Q2 and Q2

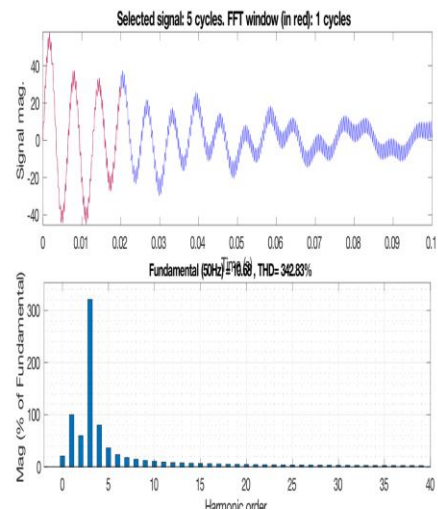& Q3 is shown in Figure 6.1. The signal transforms between 0 and 1V of the fundamental frequency.

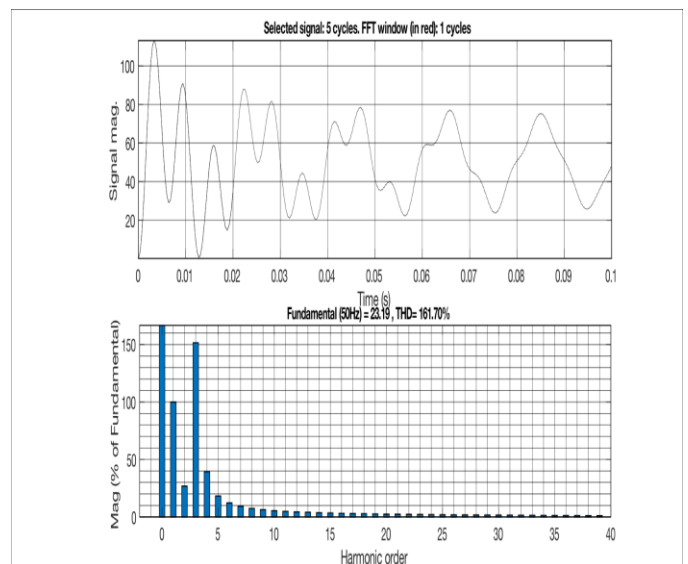Figure 6.2: FFT results of Unipolar SPWM inverter output current (Io)

Figure 6.3: FFT results of Unipolar SPWM inverter output voltage (Vo)

All waveform signals shown in Figure 6.2 &6.3 are FFT analysis of both output voltage and current at a switching frequency of 2 kHz. Modulation amplitude is 0.1 at 100V supply. From Figure 6.2, output current signal has high THD compared to output voltage as shown in the figures 6.3. When the gain is decreased the output voltage and current waveforms have less THD and the output waveforms are more sinusoidal.

B. *Hysteresis –Band Current Control Pulse Width Modulation (HCCPWM)*

Hysteresis-Band PWM is shown in Figure 7, is basically an instantaneous feedback current control method of PWM, where

the actual current continually tracks the command current within a hysteresis band [29]. As shown in Figure 7, the switching transistors Q1&Q4, and Q2&Q3, the input current *Is* is forced to follow a reference shape. The HCC causes the AC current vector to track reference voltage with almost negligible time and insensitivity to line voltage and load parameter variations. The peak current ripple and switching frequency are related to the bandwidth of the hysteresis band. An optimum band that maintains a balance between the harmonic ripple and inverter switching loss is desirable. The hysteresis-band PWM region can be smoothly transitioned to square wave voltage mode through the quasi PWM region. The phase deviation causes problems in high performance machine control of course isolated neutral load create additional distortion of the current wave [3]
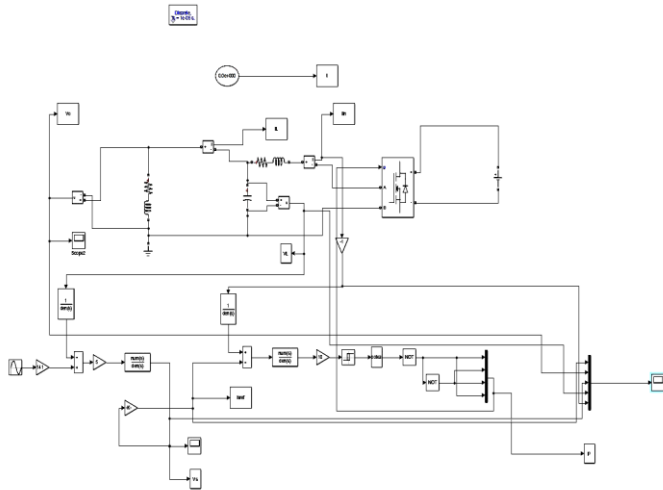

Figure 7: Mat lab HCC Controller

AS shown in Figure 7, the following are the parameters used:
The line inductance and resistance are 1mH & 1mΩ, load resistance of 100Ω and capacitance of 1000μF, DC voltage of 100V at a switching frequency of 2kHz and fundamental frequency of 50Hz.
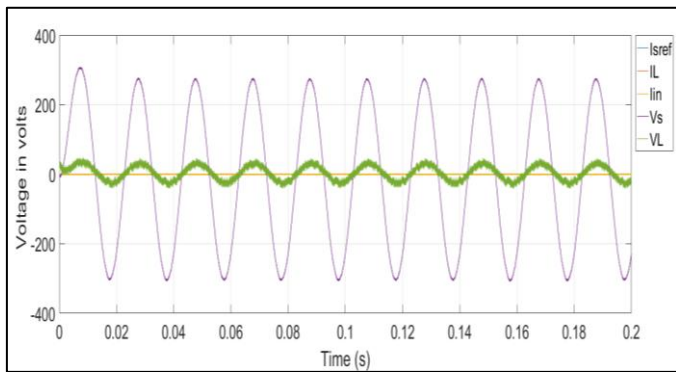

Figure 7.1: HCC waveform signals

Figure 7.1 show voltage and current waveform signals of reference current (Isref), load current (IL), input current (Iin),

supply voltage (Vs) and load voltage (VL). Vs switches between zero and positive or zero to negative voltage. Vs is 250v and is sinusoidal in shape. Isref tracks the command current with the hysteresis band. VL is the load voltage or output voltage resulting from the load.
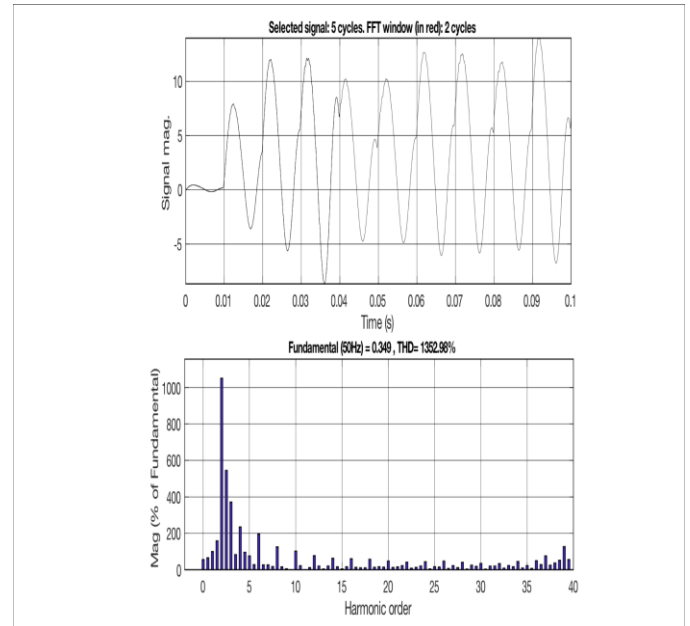

Figure 7.2: Simulated performance of HCC PWM inverter output voltage (Vo) (fs=2kz).

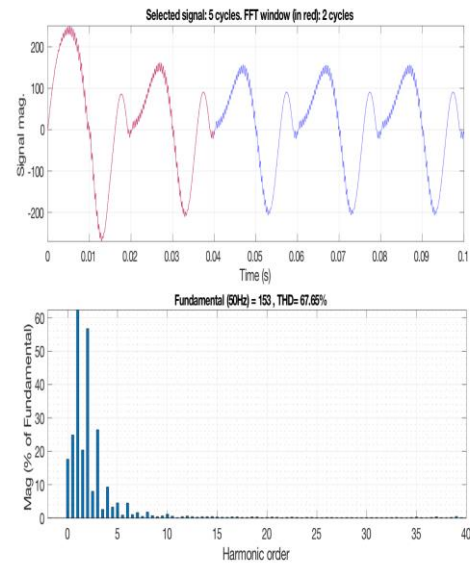Figure 7.3: Simulated performance of HCC PWM inverter output current (Io) (fs=2kz).

As shown in Figure 7.2 &7.3, FFT analysis of both output voltage and current at a switching frequency of 2 kHz. Modulation amplitude is 0.1 at 100V supply. Voltage and

current output have & 1352.90% & 67.65% THD. The higher the gain results, the higher THD value and vice versa.

C. Modified Sinusoidal Pulse Width Modulation(MSPWM)

The Sinusoidal Pulse Width Modulation technique with a modified controller is shown in Figure 8, less research has been done as compared to the standard SPWM. Therefore, the Modified SPWM technique have more advantages as compared to the SPWM. When using the MSPWM the pulse width does not change significantly with the variation of modulation index due to the characteristics of the sine wave. Hence the Sinusoidal PWM technique is modified so that the carrier signal is applied during the first and last 60 degrees interval per half cycle. When the fundamental component is increased the harmonic content gets improved. The main advantage of this technique is increased in fundamental component, improved harmonic characteristics, reduced number of switching power devices and decreased switching loss.
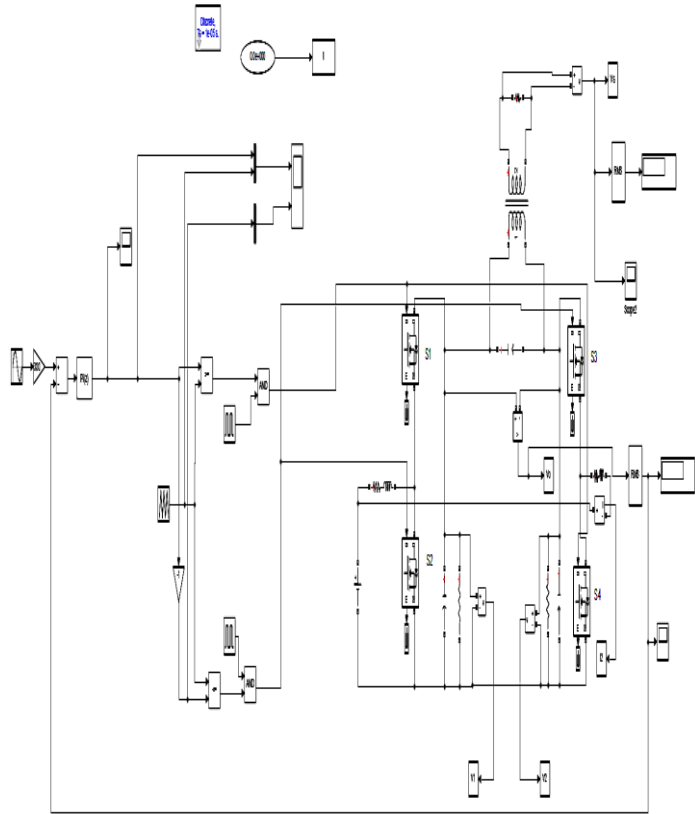

Figure 8: Modified SPWM MATLAB/ Simulink model.

AS shown in Figure 8, the following are the parameters used: The line inductance and resistance are 1mH & 1mΩ, load resistance of 100Ω and capacitance of 1000μF, DC voltage of 100V at a switching frequency of 2kHz and fundamental frequency of 50Hz.
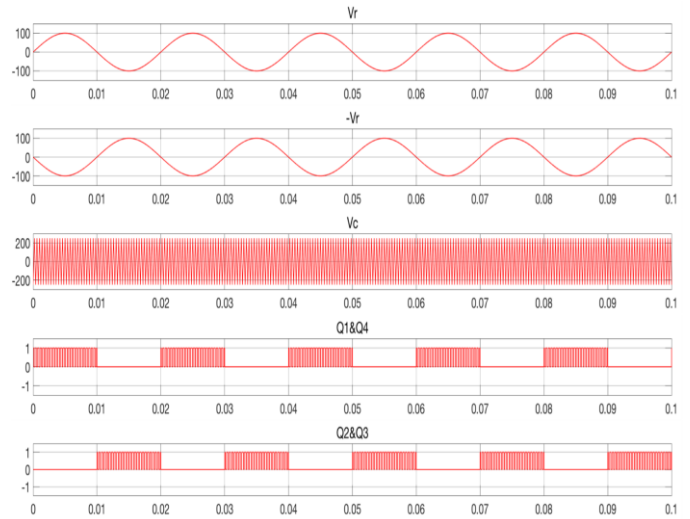

Figure 8.1: Simulated performance of Unipolar PWM inverter (fs=2kHz)

Unipolar SPWM switching scheme that is shown in Figure 8.1 was achieved by comparing two Sinusoidal reference waveforms (Vr and -Vr) that have the same frequency and magnitude but with 180°phase shifted compared with triangular signal (Vc). The output generated by switches Q1 & Q2 and Q2 & Q3 is shown in Figure 8.1. The signal transforms between 0 and 1 V of the fundamental frequency.
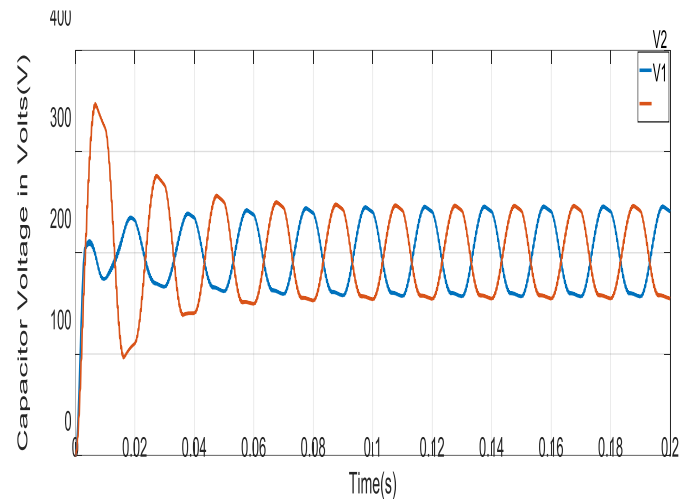
Figure 8.2: Capacitor maximum voltage (V_1 & V_2).

The capacitor voltages (V_1 & V_2) of the boost inverter are maintained at constant magnitude for both load and ripple voltage. The phase shift is maintained at 180° between the two capacitor voltages (V_1 & V_2) of the bi-directional boost DC-DC converters. Hence the proposed controller regulates the capacitor voltages of boost inverter for any variations in load of up to a set maximum value.
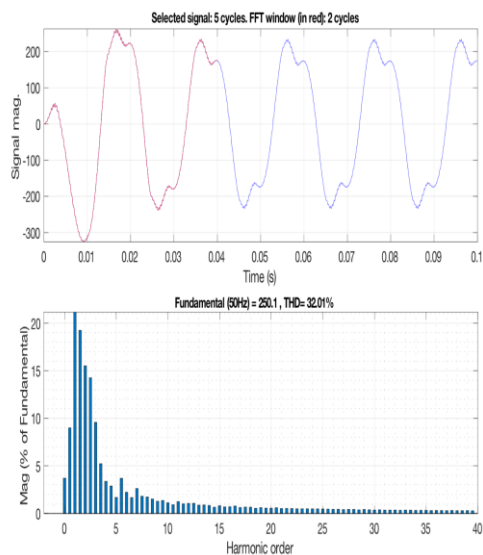
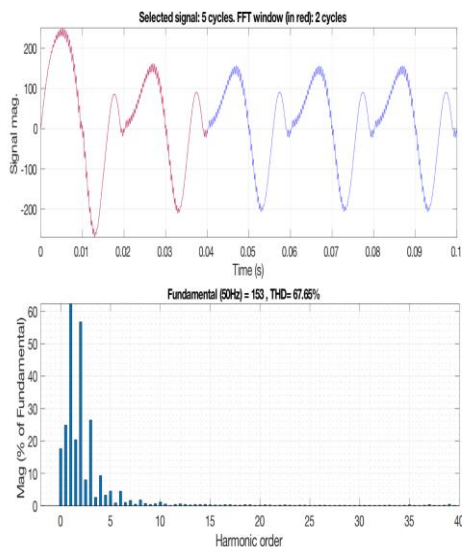Figure 8.3: FFT results of Unipolar MSPWM inverter output voltage (Vo)

Figure 8.4: FFT results of Unipolar MSPWM inverter output current (Io)

All waveform signals shown in Figure 8.4 &8.5 are FFT analysis of both output voltage and current at a switching frequency of 2 kHz. Modulation amplitude is 0.1 at 100V supply. Current output signal has high THD compared to output voltage as shown in the figures Figure 8.4 &8.5. When the gain is at minimum value the resultant output (Vo &Io), have less THD and more sinusoidal waveform is obtained.

IV. CONCLUSION

MATLAB/Simulink software was used to designed, evaluate and analyze the output voltage and current results between the three most-used modulation techniques. The modulation techniques which have been in use are SPWM, HCCPWM and MSPWM. These PWM techniques are used in multilevel inverters. The main aim of this study is to obtain output voltage and current waveform having a minimum Total Harmonic Distortion (THD). Unipolar switching scheme was used in both SPWM and MSPWM techniques. Results obtained from MATLAB /Simulink were analyzed. Sinusoidal Pulse Width Modulation technique was identified to be the simpler method to implement in a cost-effective manner. SPWM technique have high THD. As shown in Figure 6.2 & 6.3, output current and voltage of SPWM are 342.83 % & 161.70 % THD. This indicate that the amount of harmonic content is high at both output current and voltage waveform. SPWM scheme has high losses and poor linearity in voltage and current control. As shown in Figure 7.2 & 7.3, HCCPWM produced output current and voltage of 67.65 % & 1352 % THD. In this scheme the switching losses are reduced and the linearity of voltage and current control are better compared to SPWM. HCCPWM has Unstable PWM frequency as its main disadvantage. Modified Sinusoidal PWM technique produces output current and voltage of 32.01% & 67.65 % of THD as shown in Figure 8.3 & 8.4. This scheme has low losses and voltage and current control is more linear compared to SPWM and HCCPWM. Same parameters were used for all three modulation techniques that were simulated. By comparing the results between SPWM, HCCPWM & MSPWM techniques in a single-phase bridge inverter, the best sinusoidal output signal and low THD is produced by MSPWM technique.

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