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Speed control of three phase induction motor drive using SVPWM control scheme

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***Abstract*— This paper present a DSP based V/f open loop and close loop induction motor AC drive with SVPWM modulating scheme. This paper describes comparison of SVPWM and SPWM modulating techniques with motor load and choke load. Simulation results are obtained using PSIM Software with a 45kW (60 HP) motor drive and analysis of THD (Total Harmonic Distortion) and FFT (Fast Fourier Transform) in Line Voltage and Line Current for both modulating techniques. From results it is concluded that SVPWM can utilize more dc link voltage than SPWM and we get more output voltage. In SVPWM THD in line voltage & line current is also less than SPWM. Also this paper describes V/f open loop and close loop induction motor control techniques with SVPWM modulating scheme for controlling of three phase induction motor drive and getting constant flux/torque upto rated speed. Simulation results are obtained using PSIM Software with a 5.5kW (7 HP) motor drive and analysis of motor speed, motor voltage, motor current, THD and FFT (in Line Voltage and Line Current) and motor torque. The principle is explained qualitatively and extensive experiments have been carried out to verify and validate the proposed algorithm. A floating-point C2000 family DSP 28335 from Texas Instruments was used as the controller to implement the proposed control algorithm.**

***Index Terms*—SPWM, SVPWM, V/f open loop, V/f close loop, Three phase inverter and DSP**

I. INTRODUCTION

The variable frequency drive has wide scope in induction motor drive for speed control, energy saving, easy control and cost optimization. These drives come with different designs using various power converter topologies and control scheme. Each design offers some unique features but also has some limitation in speed control. So speed control does become an important in AC drive. The high switching techniques give better quality output but at the expense of the switching losses. Different PWM techniques have different switching pattern and best technique need to be implemented. This thesis focuses on step by step implementation of SVPWM algorithm for induction motor control and to improve the efficiency of VFD drive.

AC drive (VFD) is capable of adjusting both voltage and speed of an induction motor, synchronous motor and etc. VFD (variable frequency drive) referred to variety of names, such as adjustable speed drives, adjustable frequency drives or variable frequency inverters and variable speed drive (VSD). It is more efficient above 90% at full load.

The Space Vector Pulse Width Modulation of a two level inverter provides the additional advantage method, more DC bus voltage utilization and to generate less THD compare to sinusoidal PWM. Main advantage of using SVPWM in VFD is to get $2/\sqrt{3}$ time more output voltage than SPWM.

II. SPWM

In this modulation technique, to get the desired three phase balanced voltages three sinusoidal reference waveforms are used as control and triangular carrier of desired frequency is used for the comparison. When the reference is greater than the carrier, top switch is turned on at that time the voltage output is (Vdc /2) and when bottom switch is on it is (-Vdc/2). The amplitude of the phase and line voltage depends on the magnitude of the reference and carrier wave. The carrier wave magnitude is kept constant and reference magnitude is varied. Equation 1 is the ratio of modulation index and equation 2 is the ratio of modulation index.

$$\mathrm{Mi} = \frac{\mathrm{Vreference}}{\mathrm{Vcarrier}} \tag{1}$$

$$\mathrm{Mf} = \frac{\mathrm{fs}}{\mathrm{f1}} \tag{2}$$

Where fs is the switching frequency and f1 is the fundamental frequency. In the case of three phase inverters only harmonics in the line so the line voltages are concern. The inverter line-to-line voltage VAB can be determined by VAB = VAN – VBN. The switching frequency of the active switches in the two-level inverter can be found from $fsw = f_{cr} = f_m \times m_f$.

The harmonics in the pole voltages are identical and hence in the line voltage the harmonics appear as sidebands of mf. If mf is odd, only odd harmonics exist. Equation 3 is represents the harmonics.

$$n = jm_f \pm k \tag{3}$$

where j = 1,3,5…for k = 2,4,6… and j = 2,4,6…for k = 1,3,5… Hence harmonics are at $m_f \pm 2$, $m_f \pm 4$, $2m_f \pm 1$, $2m_f \pm 5$. The Harmonic analysis for the line voltage is shown in table 1. The modulation index range is from 0 < mi <1. It is known as linear modulation. In this range the fundamental voltage component varies linearly with mi. Equation 4 and Equation 5 are represents the output line voltage.

$$\text{Line voltage} = \sqrt{3} * \frac{Vdc}{2} \tag{4}$$

$$\text{Line voltage} = 0.612 * ma * Vdc \tag{5}$$

Table 1 Harmonic analysis for the line voltage

Nth harmonics	**mi = 0.2**	**mi = 0.4**	**mi = 0.6**	**mi = 0.8**	**mi = 1**
1	0.121	0.243	0.366	0.487	0.612
mf ± 2	0.009	0.037	0.08	0.134	0.195
mf ± 4	-	-	-	0.005	0.011
2mf ± 1	0.116	0.2	0.227	0.192	0.111
2mf ± 5	-	-	-	0.008	0.02
3mf ± 2	0.027	0.085	0.124	0.108	0.038
3mf ± 4	-	0.007	0.029	0.064	0.096
4mf ± 1	0.1	0.096	0.005	0.064	0.042
4mf ± 5	-	-	0.021	0.051	0.073
4mf ± 7	-	-	-	0.01	0.03

In overmodulation harmonics appear centered around m_f and its multiples. Hence the line voltages range with modulation index mi vary from 1 to 3.24 is 0.612 * mi * Vdc to 0.78 * mi * Vdc.

III. SVPWM [5]

Step 1: Determination of theta, V_{alpha}, V_{beta} and sector:

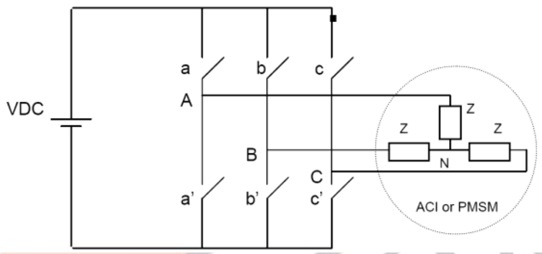

Figure 1: Power bridge for a three-phase voltage source inverter

There are eight possible combinations of on and off states of the upper switches. These combinations and the resulting instantaneous output line-to-line and phase voltages, for a dc bus voltage of V_{DC}, are shown in Table 2.

Table 2: Instantaneous output line-to-line and phase voltages

c	b	a	V_{AN}	V_{BN}	V_{CN}	V_{AB}	V_{BC}	V_{CA}
0	0	0	0	0	0	0	0	0
0	0	1	$2V_{DC}/3$	$-V_{DC}/3$	$-V_{DC}/3$	V_{DC}	0	$-V_{DC}$
0	1	0	$-V_{DC}/3$	$2V_{DC}/3$	$-V_{DC}/3$	$-V_{DC}$	V_{DC}	0
0	1	1	$V_{DC}/3$	$V_{DC}/3$	$-2V_{DC}/3$	0	V_{DC}	$-V_{DC}$
1	0	0	$-V_{DC}/3$	$-V_{DC}/3$	$2V_{DC}/3$	0	$-V_{DC}$	V_{DC}
1	0	1	$V_{DC}/3$	$-2V_{DC}/3$	$V_{DC}/3$	V_{DC}	$-V_{DC}$	0
1	1	0	$-2V_{DC}/3$	$V_{DC}/3$	$V_{DC}/3$	$-V_{DC}$	0	V_{DC}
1	1	1	0	0	0	0	0	0

From equation 6 the line and phase voltage of three phase quantity, we get the V_{alpha}, V_{beta} components using Clarke transformation. Switching patterns, corresponding space vectors and their (V_{alpha}, V_{beta}) components are shown in table 2.

$$\begin{bmatrix} V_{s\alpha} \\ V_{s\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} \tag{6}$$

The coefficient 2/3 is arbitrarily chosen, commonly used value 2/3 or $\sqrt{2/3}$. The main advantage of using 2/3 is that the magnitude of the two phase voltage will be equal to that of three phase voltages after the transformation.

Table 3: Switching patterns, corresponding space vectors and their (V_{alpha}, V_{beta}) components

c	b	a	$V_{s\alpha}$	$V_{s\beta}$	Vector
0	0	0	0	0	O_0
0	0	1	$\frac{2}{3}V_{DC}$	0	U_0
0	1	0	$-\frac{V_{DC}}{3}$	$\frac{V_{DC}}{\sqrt{3}}$	U_{120}
0	1	1	$\frac{V_{DC}}{3}$	$\frac{V_{DC}}{\sqrt{3}}$	U_{60}
1	0	0	$-\frac{V_{DC}}{3}$	$-\frac{V_{DC}}{\sqrt{3}}$	U_{240}
1	0	1	$\frac{V_{DC}}{3}$	$-\frac{V_{DC}}{\sqrt{3}}$	U_{300}
1	1	0	$-\frac{2}{3}V_{DC}$	0	U_{180}
1	1	1	0	0	O_{111}

The eight basic space vectors defined by the combination of the switches are also shown in Figure 2

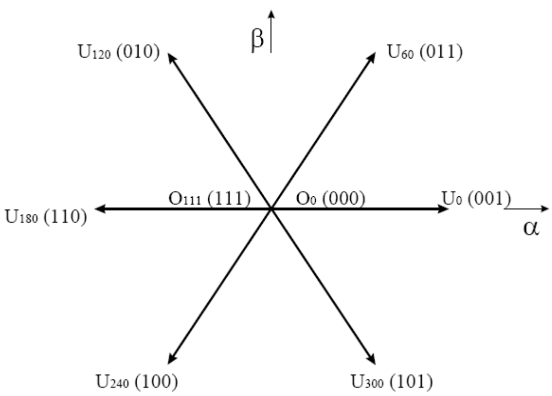

Figure 2: Space vector diagram for a two level inverter

Step 2: Calculation of vector time t1 and t2 incorporated with sector:

The t1 and t2 are respective durations in time, vectors U_{alfa} and U_{beta} applied within period T. We get constant value of X, Y, Z from U_{alfa} and Ubeta which is shown in equation 7,8 and 9.

$$X = U_{beta} \tag{7}$$

$$Y = \frac{1}{2}\left(\sqrt{3}U_{alfa} + U_{beta}\right) \tag{8}$$

$$Z = \frac{1}{2}\left(-\sqrt{3}U_{alfa} + U_{beta}\right) \tag{9}$$

t1 and t2 definitions for different sectors in terms of X, Y and Z constant are shown in table 4.

Table 4: t1 and t2 definitions for different sectors in terms of X, Y and Z variables

Sector	**U_0,U_{60}**	**U_{60},U_{120}**	**U_{120},U_{180}**	**U_{180},U_{240}**	**U_{240},U_{300}**	**U_{300},U_0**
t_1	-Z	Z	X	-X	-Y	Y
t_2	X	Y	Y	Z	-Z	-X

Step 3: Determination of the duty cycle (Motor per phase reference voltage) t_{aon}, t_{bon} and t_{con}:

The duty cycle t_{aon}, t_{bon} and t_{con} are calculated as per the equation 10,11 and 12.

$$t_{aon} = \frac{PWMPRD - t_1 - t_2}{2} \tag{10}$$

$$t_{bon} = t_{aon} + t_1 \tag{11}$$

$$t_{con} = t_{bon} + t_2 \tag{12}$$

Step 4: Assignment right duty to the right motor phase (Ta, Tb and Tc):

According to sectors and reference voltages shown in table 5. assignment right duty to right motor phase which is shown in figure 3.

Table 5: Right duty cycles assign to the right motor phase

Sectors	**U_0,U_{60}**	**U_{60},U_{120}**	**U_{120},U_{180}**	**U_{180},U_{240}**	**U_{240},U_{300}**	**U_{300},U_0**
T_a	t_{aon}	t_{bon}	t_{con}	t_{con}	t_{bon}	t_{aon}
T_b	t_{bon}	t_{aon}	t_{aon}	t_{bon}	t_{con}	t_{con}
T_c	t_{con}	t_{con}	t_{bon}	t_{aon}	taon	t_{bon}

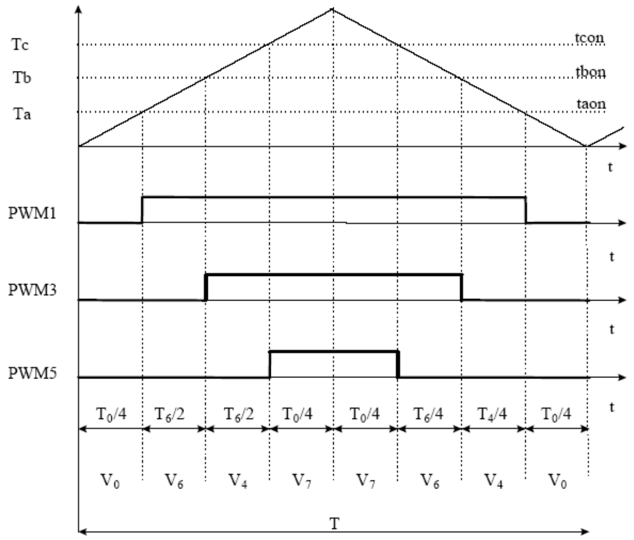

Figure 3: Stator voltage reference generating duty for motor phase

Equation 13 and equation 14 are represents the output line voltage in SVPWM.

$$\text{Line voltage} = \sqrt{3} * \frac{Vdc}{2} \tag{13}$$

$$\text{Line voltage} = 0.707 * ma * Vdc \tag{14}$$

V_{Lmax} (SVPWM)/ V_{Lmax} (SPWM) = 1.155 which indicated 15.5% more dc utilization.

IV. Open loop and close loop V/f drive

Open loop and close loop V/f drive with current control is shown in figure 4.

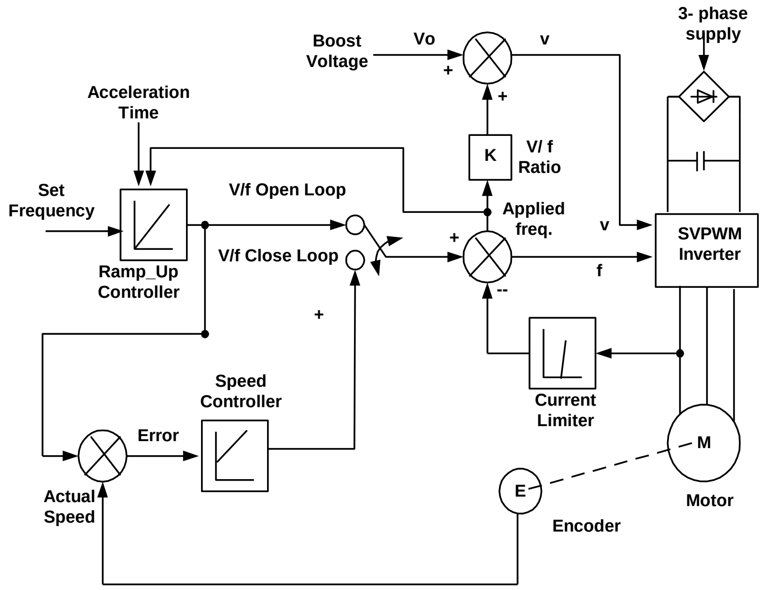

Figure 4: Open loop and close loop V/f drive with current control

V/f open loop (Switch ON to the V/f open loop side):

A frequency reference sets the inverter frequency f. The inverter voltage V is set according to the relation V = K + Vo to operate the machine at nearly constant flux up to the base speed. At the base speed, the motor terminal voltage saturates. The machine operates at a constant terminal voltage above the base speed. The offset voltage Vo is chosen to produce the nominal flux at zero speed and the constant K is chosen to get the rated voltage at the base speed.

V/f close loop (Switch ON to the V/f close loop side):

The error between the set speed and actual motor speed (Encoder feedback) is processed through a PI speed controller. The PI speed controller gives corrected applied frequency to the inverter. The inverter voltage V is set according to the relation $V = K + V_o$ to operate the machine at nearly constant flux up to the base speed.

Current-limit control is provided to prevent the motor current from exceeding a safe value. The stator current is sensed by a current sensor. As long as is less than the permissible value, the current limiter output remains zero and motor voltage is set according to signal V. Whenever stator current crosses the permissible value, the current limiter output reduces motor voltage, which reduces stator current. Thus, the drive operates around a maximum value of stator current, until the speed reaches a value for which stator current lower than the permissible value.

In the absence of the ramp up controller with acceleration time, a step change in speed command will cause the motor slip to exceed the breakdown value. The motor current will tend to exceed the safe value, but will be prevented from doing so by the current-limit control. The motor terminal voltage will decrease, reducing the motor torque. This may lead to unstable operation and the motor may damage. Therefore, the set frequency is applied through a ramp up controller. The inverter frequency now changes slowly, allowing the motor speed to track the changes in frequency. The ramp up controller, however, slows down the transient response.

V. SIMULATION AND HARDWARE RESULTS

Simulation result of V/f open and close loop with SVPWM techniques (Motor Load):

V/f open loop and close loop simulation circuit with motor load shown in figure 5.

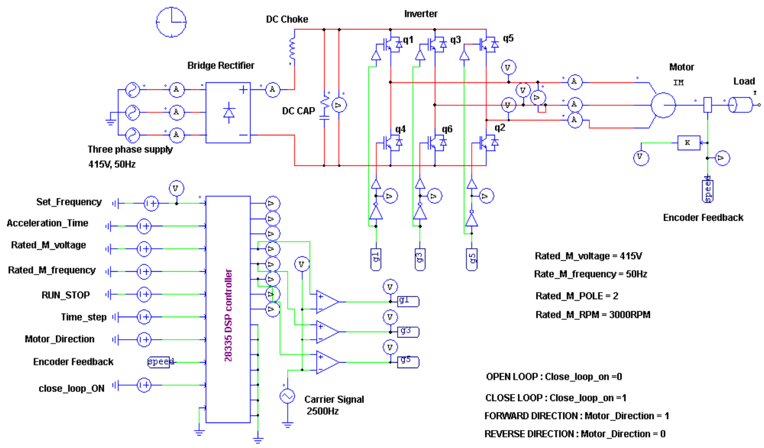

Figure 5: V/f open loop and close loop with motor

In V/f open loop, set the inverter frequency, we get motor output voltage based on the V/f curve. This scheme is simulated using simplified C block of PSIM software. C programming has been developed for SVPWM and V/f scheme using simplified C block of PSIM. V/f curve change based on the motor parameter like motor voltage and motor frequency for maintain V/f ratio constant. The set frequency, motor speed, line voltage, line current, FFT and THD of line voltage wave form shown in figure 6, 7, 8 and 9.

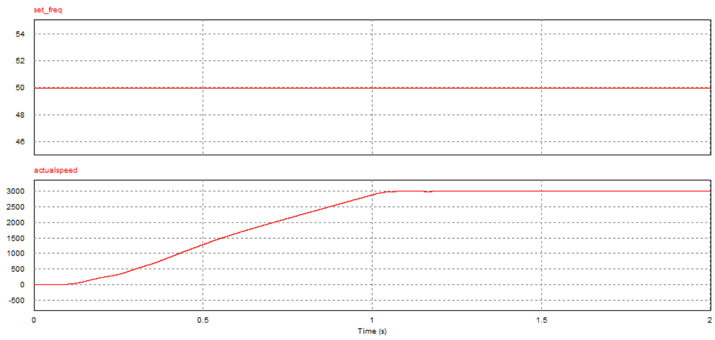

Figure 6: Set frequency and motor speed waveform: Set Freq = 50Hz, Motor speed = 3000rpm, Scale: X axis: 1 unit = 0.5 sec, Y axis: 1 unit = 2Hz, 500rpm.

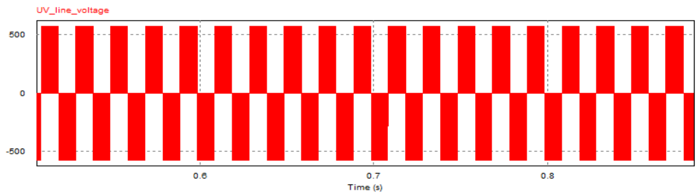

Figure 7: Line voltage waveform: Line voltage = 434VDC, Scale: X axis: 1 unit = 0.1 sec, Y axis: 1 unit = 500V

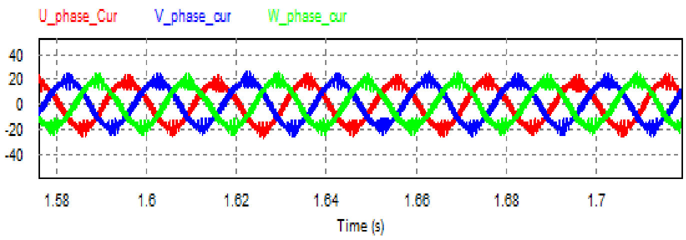

Figure 8: Output current waveform: current= 14.74Amp, Scale: X axis: 1 unit = 0.05 sec, Y axis: 1 unit = 20A

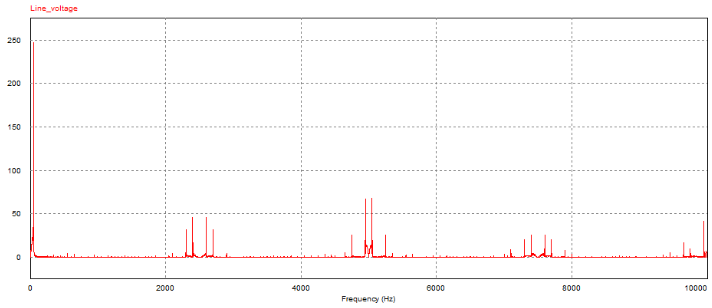

Figure 9: FFT spectrum, THD = 73%, Scale: X axis: 1 unit = 2000Hz, Y axis: 1 unit = 50V

Encoder feedback is given to the ac drive 28335 DSP controller. Based on the error, PI controller give corrective frequency reference to the inverter.

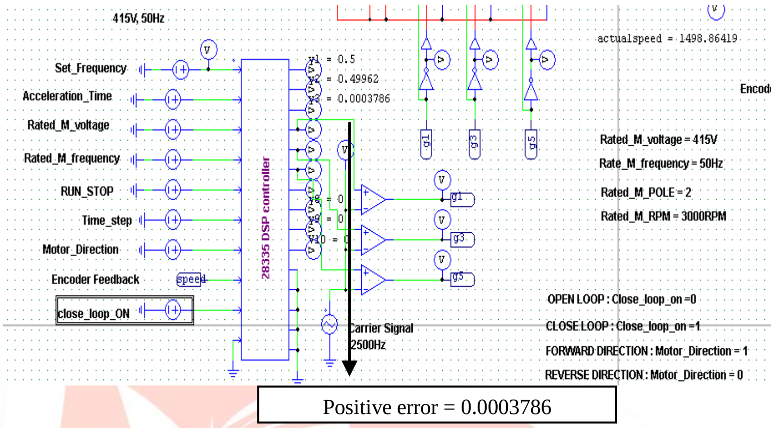

Figure 10: V/f close loop with motor load C block with positive error

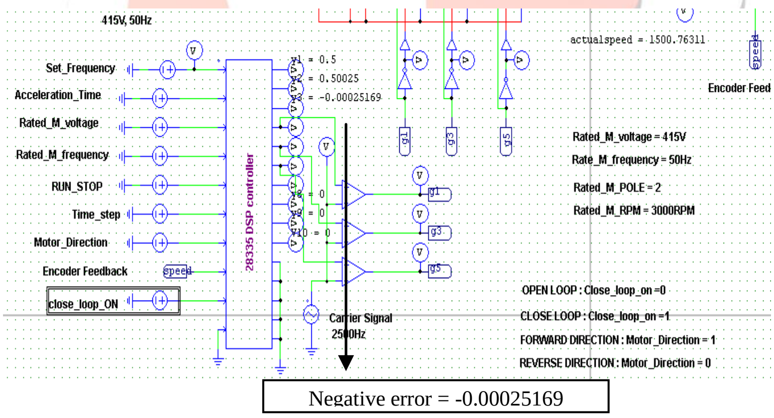

Figure 11: V/f close loop with motor load C block with negative error

Comparison of SPWM and SVPWM:

The simulation comparison results of SVPWM and SPWM are included in table 6.

Table 6: Right duty cycles assign to the right motor phase

Condition : 4-pole 45kw motor data							
Sr no.	Modulation Index	SPWM			SVPWM		
		Voltage	DC Volt	THD	Voltage	DC Volt	THD
1	0.95	412	573	74%	434	573	64%
2	0.78	375	572	93%	392	572	85%

Hardware result:

TMS32028335 based control card has a docking station with access to all control CARD signals, breadboard areas, RS-232, JTAG connector, and on board USB JTAG emulation. Control card is complete with Code Composer Studio™ IDE v5.3.0 Version. It has below feature.

150 MHz (6.67-ns Cycle Time), Floating point DSP
High-Performance 32-Bit CPU (TMS320C28x)
On-Chip Memory: 256K x 16 Flash, 34K x 16 SARAM
12-Bit ADC, 16 Channels
Three 32-Bit CPU Timers
Up to 88 Individually Programmable, Multiplexed GPIO Pins with Input Filtering
Enhanced Control Peripherals; Up to 18 PWM Outputs

With using the TMS32028335, generating SVPWM pulses for each phase which is shown in figure 12. Generating V/f voltage according to set frequency which is shown in figure 13.

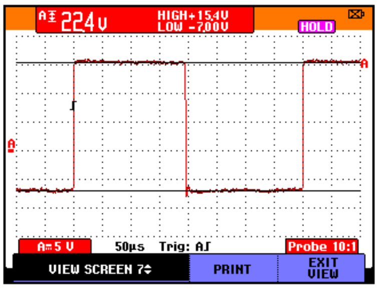

Figure 12: Output line voltage between U and V phase at channel-A

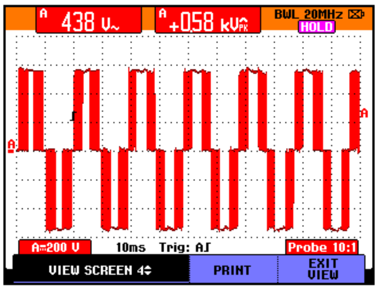

Figure 13: Output line voltage between U and V phase at channel-A

VI. CONCLUSION

As per simulation results, we find out the Space Vector Pulse Width Modulation of a two level inverter provides the additional advantage method, more DC bus voltage utilization and to generate less output current and voltage THD compare to sinusoidal PWM. The main advantage of using SVPWM in VFD is to get 15% more output voltage than SPWM. In V/f induction motor control techniques, get constant motor torque upto rated speed. AC drive with V/f techniques solve many application likes fan, pumps, compressor, conveyor and etc, save energy to reduce the cost. V/f drive with close loop techniques is used, where the load (torque) changing require with constant speed. Current limit function with VFD is protects the motor. Proper components selection (Hardware design) of VFD can give better VFD life and ultimate reduce the cost.

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