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Performance Analysis of three phase induction motor drive for Various PWM control Methods

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Abstract - This paper presents performance analysis of three phase induction motor drive for various control methods. Three phase inverters are mostly used in industries for adjustable and variable speed three phase induction motor drive systems. The working of three phase induction motor drive system is discussed. The simple method of generation of PWM signals in different modes of operation using single timer feature of PIC microcontroller are discussed and presented. Four different PWM control methods and there implementation using microcontroller chip to operate three phase inverter in four different modes is discussed. The desired control signals are generated using PIC microcontroller and applied to three phase inverter through driver circuit. Three phase inverter performance parameters are determined and compared for single pulse PWM modes such as simple 120^0 conduction mode, 180^0 conduction mode, and multiple pulse PWM modes such as advanced SPWM and harmonic injected PWM mode. The complete three phase induction motor drive system is designed, implemented and tested for results. The experimental and theoretical results are compared and verified.

Index Terms: - voltage source inverter, PIC Controller, 120^0 conduction, 180^0 conduction, SPWM, harmonic injected PWM, THD.

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1 INTRODUCTION

Three phase inverters are the dc to ac converters. The input dc source is either the voltage source or current source, is converted in to variable output three phase ac voltage. The output ac voltage of three phase inverter can be controlled by varying either input dc supply voltage or by varying duty cycle or modulation index of control signals. Input dc supply can be varied by using phase controlled rectifiers or by using combination of rectifiers and buck-boost converters. But this method involves double power conversion, complexity and is suitable in case inverters that are operating at fixed duty cycle or modulation index of PWM signals and fixed output frequency. There are two types of traditional inverters based on input source used in industries for variable speed drive and many other applications [1],[2]; those are a) Voltage-source inverter and b) Current-source inverter. Different PWM techniques are devised to control these inverters. The SPWM control method reduces harmonic distortion in the output signal and improves the performance of the inverter [4], [5]. The space vector modulation performance is similar to that of third harmonic injected PWM [6], [7]. But the control algorithm very complex and puts computational overheads. Like SVPWM the harmonic injected SPWM method eliminates third harmonic component from output waveform and also provides higher range of modulation index than regular SPWM modulation technique. For these advanced PWM method implementation it requires advanced hybrid controllers, which provides capability of both controller and fast computational capacity like DSP processor [8].

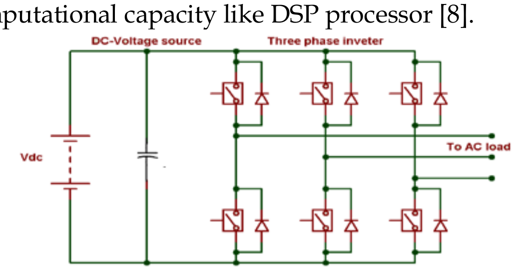

Fig. 1 Three phase voltage source inverter

The traditional three-phase, two level, voltage-source inverter is shown in Fig.1. DC link voltage produced across the input capacitor feeds the main three-phase bridge. Three phase bridge inverter circuit consists of six switches; each is composed of a power transistor and an anti-parallel diode to provide bidirectional current flow and reverse voltage blocking capability. The traditional current-source inverter (CSI) uses DC current source is formed by a voltage source such as a battery or fuel-cell stack or diode rectifier or converter in series with a large dc Inductor as shown in fig.2.

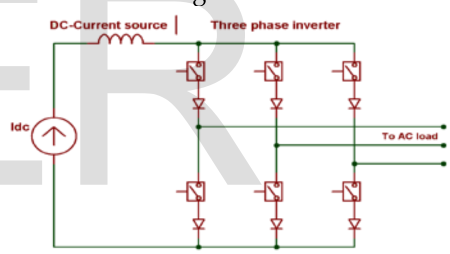

Fig. 2 Three phase current source inverter

In CSI three phase bridge inverter circuit consists of six switches; each is composed of a switching device with reverse blocking capability such as a gate-turn-off thyristor and SCR or a power transistor with a series diode to provide unidirectional current flow and bidirectional voltage blocking. In this paper the performance of three phase voltage source inverter drive is analyzed and compared for various control modes such as simple 120^0 conduction mode, 180^0 conduction mode, and advanced control modes such as SPWM mode, harmonic injected PWM mode etc. SPWM and harmonic injected SPWM is implemented for fixed modulation index and fixed frequency using lookup table method.

2. THREE PHASE IM MOTOR DRIVE SYSTEM:

Block schematic of three phase motor drive system is illustrated fig. 3. DC voltage source consist of full bridge diode rectifier with capacitor filter. Three phase inverter circuit consists of six switches connected in three legs, converts input dc link voltage in to corresponding three phase ac voltage. Microcontroller and driver circuit is used to control on/off time of switching devices in a proper sequence in a particular time used in the main inverter circuit. Microcontroller PIC18f452 is used to generate required control/PWM signal.

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PIC microcontroller is a RISC controller and has inbuilt 8/16bit timer/counters, capture compare module, 10bit ADC module, 10bit PWM module, 32kb of program memory, 1.536kb of RAM etc. The control/PWM signals are applied to the gate terminals of MOSFETs through gate driver circuit. The four input keys are interfaced to microcontroller port pins to select operating mode, to reset the controller, and to start and stop microcontroller sending control/PWM signal at port pins. The potentiometer is interfaced to ADC module to set input/output voltage and to vary the duty cycle. Controller displays both input voltage and theoretical output rms phase voltage over LCD.

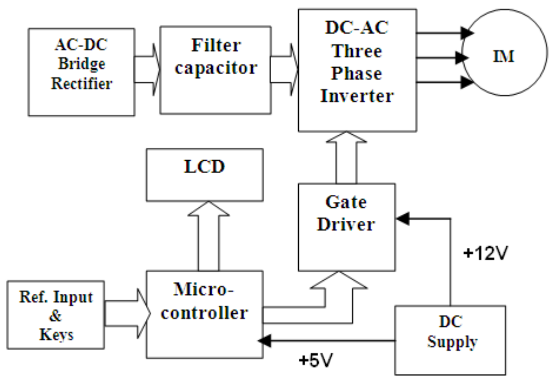

Fig. 3 Block diagram of three phase inverter fed IM drive

Gate driver circuit is designed using very fast PC923 driver IC. Gate driver IC has in built opto-isolation so doesn't need of additional isolator and buffer circuit. Input side of gate driver can be directly connected to microcontroller pin and output side to gate and source terminals of power switches. It also uses bootstrap capacitor for upper MOSFET to ensure gate voltage always higher than or equal to floating point source voltage. The complete hardware is designed to drive and control 3 phase induction motor. The complete hardware design involves the design of control circuit, gate driver circuit, low power dc supply, high power dc supply, and the inverter circuit, selection of power switches, filters etc. DC power supply is designed for obtaining 5V and 12V supply. Regulator ICs 7805 and 7812 are used to regulate the DC output at 5V and 12V respectively. 5V supply is used for the operation of the microcontroller board while 12 V supply is used for the MOSFET/IGBT gate driver circuit. LCD interface with microcontroller is provided for better user interaction with the system. LCD is interfaced to PORTC of microcontroller used to display starting message regarding project title, welcome message and provides user interface. It also displays theoretical values of output voltage for given input voltage.

3 THREE PHASE INVERTER AND CONTROL METHODS:

The circuit diagram of three phase voltage source inverter is shown in the fig. 4. The upper three MOSFETs are numbered as A, B, C and lower three are numbered as A′, B′, C′. Power MOSFETs and IGBTs are fast switching devices and there turn off time is less than a microsecond. So power MOSFET or IGBT can be used in high frequency inverters. MOSFETs (A and A′, B and B′, C and C′) in the same leg are complimentary pairs and conduct alternately. Care should be taken, that the upper and lower MOSFET in the same leg should not be turned on simultaneously to avoid cross conduction of pairs. For e.g. suppose MOSFET A is conducting in any switching cycle and MOSFET A′ is in off state. During switch changeover from A to A′, MOSFET A should be turned off first, add some delay time called as dead time and then turn on lower MOSFET A′.

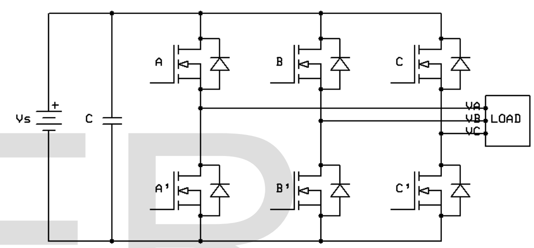

Fig. 4 Three phase inverter circuit schematic

This dead time should be two to three times the turn off time of power switch used in Inverter Bridge. Depending on type of control signals used to obtain three phase ac output voltage, there are various control methods such as single pulse PWM modes- 120^0 Conduction Mode, 180^0 Conduction Mode, and multiple pulse PWM method such as sinusoidal pulse width modulation (SPWM), and modified SPWM etc. These four methods and respective control signal generation using PIC microcontroller is described in this section.

3.1 120^0 Conduction Mode:

In 120^0 conduction mode only two power switches one from upper and one from lower switches conducts at a time in each switching cycle..

Table 1 Phase voltage, line voltage and switching pattern for 120^0 conduction mode.

State no	Switchting states	Phase voltage			Line-line voltage			Gate drive input logic						Hex code	Switching time
		Vc	Vb	Va	Vca	Vbc	Vab	C′	B′	A′	C	B	A		
1	A, B′ ON	0	-Vs/2	Vs/2	0	0	Vs	1	0	1	1	1	0	0x2e	0-3.33ms
2	A, C′ ON	-Vs/2	0	Vs/2	-Vs	0	0	0	1	1	1	1	0	0x1e	0-3.33ms
3	B, C′ ON	-Vs/2	Vs/2	0	0	Vs	0	0	1	1	1	0	1	0x1d	0-3.33ms
4	B, A′ ON	0	Vs/2	-Vs/2	0	0	-Vs	1	1	0	1	0	1	0x35	0-3.33ms
5	C, A′ ON	Vs/2	0	-Vs/2	Vs	0	0	1	1	0	0	1	1	0x33	0-3.33ms
6	C, B′ ON	Vs/2	-Vs/2	0	0	-Vs	0	1	0	1	0	1	1	0x2b	0-3.33ms
7	Zero state	0	0	0	0	0	0	1	1	1	1	1	1	0x3f	0-3.33ms

Table-1 shows line voltage, phase voltage values, and switching pattern in different switching states in 120^0 conduction mode. The details of PWM generation method for 120^0 conduction mode is described in the following line of this section. In the tables-1 to 4 A, B, C refers to upper three power switches and A′, B′, C′ refers to lower three power switches in

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inverter bridge as shown in the fig. 4. Gate driver circuit gives inverted output pulses. So in the table entries in columns A, B, C, A′, B′, C′, logic 0 indicates respective power switch ON and logic 1 indicates respective power switch OFF. There are six active states and one zero state. The PIC microcontroller is programmed to output these PWM gating signal for 120^0 conduction mode at PORTD. These PWM gate pulses are illustrated in the fig. 5 with respect to state 1 to 6 in table 1. State 7 is a zero state occurs between two consecutive active states. State switching occurs after every 60^0 i.e 3.33ms. Each active state time can be varied from 0 to 3.33ms and zero state time is equal to switching cycle (T = 3.33ms) minus active state time in each switching cycle.

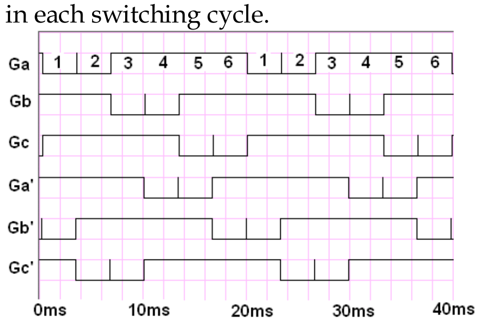

Fig. 5 Microcontroller output gate pulses for 120^0 conduction

These gate pulses are generated at PORTD using timer0 of PIC microcontroller and ADC module. Timer0 is operated in eight bit mode with prescalar 1:64 to obtain max time delay of 3.33ms. With crystal frequency fc = 20Mhz, timer0 input frequency is fc/4 = 5MHz, and with prescalar 1:64, timer0 input frequency becomes 5MHz/64 = 78.125KHz. Timer0 will increment by one after every 12.8μs and roll over after 255 count. Thus in eight bit mode maximum time delay produced will be equal to (255+1)*12.8us = 3.28ms plus state change time which is nearly equal to 3.3ms. So three phase voltage output frequency will be equal to 1/ (3.3 *6) = 50.5Hz ≈ 50Hz. A potentiometer with a series resistor tide to V_{cc} is connected to the channel 0 of 10bit ADC module which will provide maximum voltage corresponding to 255(8 bit). ADC module is right justified and only eight bit data from ADRESL is read and used to set duty cycle. Two MSB bit in ADRESH are ignored. PWM signal duty cycle can be varied from zero (T_{on} = 0ms) to one (T_{on} = 3.3ms) giving wide range of output voltage control. Output voltage can be varied from zero to maximum value in 256 steps and is sufficient to provide smooth variation. The rms phase voltage and line voltage equation [6] from the waveforms for 120^0 conduction mode is given by following equation;

$$V_{an} = \alpha * 0.4082 * V_{dc} \quad (1)$$

$$V_{LL} = \alpha * 0.7071 * V_{dc} \quad (2)$$

Where $\alpha = T_{on} / T$ is duty cycle for single pulse modulation used, and V_s is dc input voltage to the inverter. By varying the duty cycle the output voltage can be controlled.

3.2 180^0 conduction mode:

In 180^0 conduction mode three power switches out of six conducts at a time in each switching cycle. Table 2 shows various switching states, and respective phase voltage, line voltage and switching pattern in different operating states in 180^0 conduction mode. Like120^0 conduction mode there are six active states and one zero state. In both 120^0 conduction mode and 180^0 conduction mode the switching state time (last column of table-1 and table-2) can be varied between 0s to 3.33ms to vary the output voltage. The gating pulses in 180^0 conduction mode are generated in the similar way as that of for 120^0 conduction mode using timer 0 and ADC module as discussed in section 3.1. These PWM gate pulses are illustrated in the fig. 6 with respect to state 1 to 6 in table 2. State 7 is a zero state occurs between two consecutive active states. State switching occurs after switching cycle = 3.33ms and each device conduct for180^0.

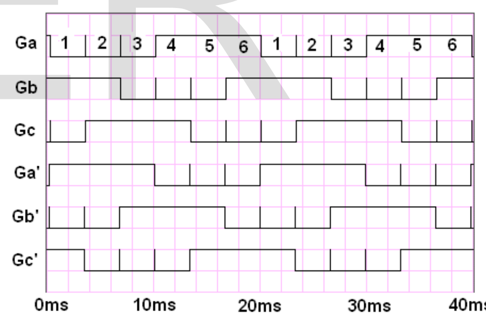

Fig. 6 Microcontroller output gate pulses for 180^0 conduction

Table 2 Phase voltage, line voltage and switching pattern for 180^0 conduction mode.

State no	Switching state	Phase voltage			Line-line voltage			Gate drive input logic						Hex code	Switching time
		Vc	Vb	Va	Vca	Vbc	Vab	C′	B′	A′	C	B	A		
1	A, B′, C ON	Vs/3	-Vs/3	Vs/3	0	-Vs	Vs	1	0	1	0	1	0	0x2a	0-3.33ms
2	A, B′, C′ ON	-Vs/3	-Vs/3	2Vs/3	-Vs	0	Vs	0	0	1	1	1	0	0x0e	0-3.33ms
3	A, B, C′ ON	-2Vs/3	Vs/3	Vs/3	-Vs	Vs	0	0	1	1	1	0	0	0x1c	0-3.33ms
4	A′, B, C′ ON	-Vs/3	2Vs/3	-Vs/3	0	Vs	-Vs	0	1	0	1	0	1	0x15	0-3.33ms
5	A′, B, C ON	Vs/3	Vs/3	-2Vs/3	Vs	0	-Vs	1	1	0	0	0	1	0x31	0-3.33ms
6	A′, B′, C ON	2Vs/3	-Vs/3	-Vs/3	Vs	-Vs	0	1	0	0	0	1	1	0x23	0-3.33ms
7	Zero state	0	0	0	0	0	0	1	1	1	1	1	1	0x3f	0-3.33ms

The rms phase voltage and line voltage equation [6], [7] from the waveforms for 180^0 conduction mode is given by following equation

$$V_{an} = \alpha *0.4714* V_{dc} \quad (3)$$

$$V_{LL} = \alpha *0.8165* V_{dc} \quad (4)$$

Where α is duty cycle of PWM wave.

3.3 Sinusoidal PWM control (SPWM):

SPWM is a multiple pulse width modulation technique in which the width of pulses varied in accordance with sinusoidal modulating signal. Table 3 shows various switching states, and respective phase voltage, line voltage and switching pattern for SPWM generation. Switching

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pattern for SPWM generation in table 3 is same as that of table 2 for 180^0 conduction except two extra zero states are added in last two rows. The letters A, B, C refers to upper three switching devices and A′, B′, C′ refers to lower three switching devices in three arms of the main inverter circuit in fig.3. Two devices in the same arm should not be switched on simultaneously. In traditional inverters this state is called shoot-through state and results in damage of the inverter switches. As shown in table 3 PWM for three phase inverter consists of six active states 1 to 6 and three zero states. The respective PWM code in hex is shown in the right side last column. PIC microcontroller is programmed to generate and output this PWM pattern at the PORTD at regular time instances provided by timer. All PWM signals are complemented when passed through gate drive circuit. Thus bit 0 in Table1 implies that particular switch is ON and bit 1 implies OFF switch in each PWM state. Three phase SPWM and harmonic injected PWM signal generation is more difficult as compared to control signal generation for 120^0 conduction mode and 180^0 conduction mode.

Table 3 Phase voltage, line voltage and switching pattern for various states in SPWM mode

State no	Switching state	Phase voltage			Line-line voltage			Gate drive input logic						Hex code
		Vc	Vb	Va	Vca	Vbc	Vab	C′	B′	A′	C	B	A	
1	Active state1	Vs/3	-2Vs/3	Vs/3	0	-Vs	Vs	1	0	1	0	1	0	0x2a
2	Active state2	-Vs/3	-Vs/3	2Vs/3	-Vs	0	Vs	0	0	1	1	1	0	0x0e
3	Active state3	-2Vs/3	Vs/3	Vs/3	-Vs	Vs	0	0	1	1	1	0	0	0x1c
4	Active state4	-Vs/3	2Vs/3	-Vs/3	0	Vs	-Vs	0	1	0	1	0	1	0x15
5	Active state5	Vs/3	Vs/3	-2Vs/3	Vs	0	-Vs	1	1	0	0	0	1	0x31
6	Active state6	2Vs/3	-Vs/3	-Vs/3	Vs	-Vs	0	1	0	0	0	1	1	0x23
7	Zero state 1	0	0	0	0	0	0	0	0	0	1	1	1	0x07
8	Zero state 2	0	0	0	0	0	0	1	1	1	0	0	0	0x38
9	Zero state 3	0	0	0	0	0	0	1	1	1	1	1	1	0x3f

There are various PWM schemes such as a) regular sampled right/left aligned, b) symmetrical/center aligned c) alternating zero state PWM. In symmetrical/center aligned PWM method each PWM cycle consists of two active states and three zero states. Center aligned PWM method gives lowest harmonics in output voltage and current as compared to other PWM methods, but the switching losses are high due to more number of state switching in each cycle [2]. Right/left aligned PWM method performance is similar to center aligned and also provides freedom of adding number of zero states and type of zero state in each PWM cycle. It can be generated using two active states and one or two zero states in each PWM cycle. In order to reduce switching losses regular sampled left aligned PWM signal is generated which consists of the two active states and one zero state.

Switching occurs after each active state and zero state. There are three types of zero states as shown in table 3, one in which all upper three switches are turned off, lower switches are turned on state 7, second one in which all upper three switches are turned on and lower switches are tuned off state 8, second, and third one in which all six switches are turned off state 9. Microcontroller uses pre-calculated pulse width duty values for fixed modulation index and frequency stored in look up table. Look up table consists of pulse width data values corresponding to first active state, second active state, and zero state arranged sequentially for ease of access. These PWM pulse width duty values corresponding to one cycle of sinusoidal signal are determined for fundamental frequency f_m = 50Hz and PWM frequency f_c = 10.8KHz. In order to reduce computational overheads, difference PWM pulse with data values are generated in such a way that it can be used to load in timer directly from the look up table/array. The number of PWM pulses per cycle is equal to f_c/f_m. Where f_c is carrier frequency and f_m is modulating signal frequency.

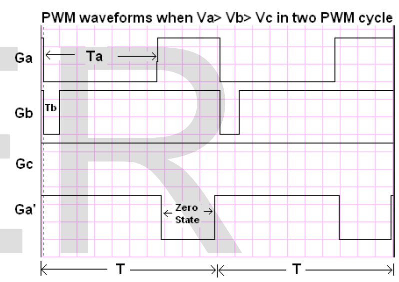

Fig. 7 Regular sampled, left aligned SPWM waveform for two PWM cycles

This number should be divisible by three in order to obtain synchronous three phase PWM waveforms. For example if f_c = 10.8 KHz and f_m = 50Hz then number of pulses per cycle is equal to 216. This number is divisible by three 216/3 = 72. The SPWM waveforms for two PWM cycles when instantaneous phase voltage V_a is greater than V_b and V_b greater than V_c are shown in the fig. 7. Ga, Gb, and Gc are gate triggering pulses for upper three switches while Ga′, Gb′ and Gc′ respectively are gate triggering pulses for lower three switches in the inverter three arms. Gb′, Gc′ waveforms are not shown in fig. 7. As discussed above each PWM cycle involves two active states and one zero state. While generating PWM pattern microcontroller first outputs switching pattern corresponding to lowest time active state e.g. 0x1c:T_b, after time T_b microcontroller outputs switching pattern corresponding to next active 0x0e:(T_a - T_b), and after second active state T_a microcontroller outputs switching pattern corresponding to zero state e.g. 0x3f or 0x27:T- (T_a + T_b).The dead time is provided during switching from one switching state to another through program. Determination of PWM pulse width data for single cycle manually requires large number of calculations and a lot of time. To avoid this calculation part completely and to obtain pulse width values

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directly for any given modulation index and carrier frequency a C code is written in Turbo C and used. The rms value of phase voltage and line voltage is given by;

$$V_{ac} = M.\frac{Vdc}{2\sqrt{2}}$$

$$V_{an} = 0.3536*M*V_{dc} \qquad (5)$$

$$V_{LL} = 0.612*M*V_{dc} \qquad (6)$$

3.4 Harmonic injected PWM control:

One of the disadvantages of regular SPWM method is it produces lower fundamental voltage at the output of the inverter. So to increase the amplitude of fundamental component there are various advanced PWM control methods such as trapezoidal modulation, delta modulation, staircase modulation, stepped wave modulation, harmonic injected modulation amplitude. Here harmonic injected modulation technique is used to verify the performance of three phase induction motor drive. The three phase PWM signal is generated with respect to third harmonic (16%) injected sinusoidal signal. The three phase PWM signal are generated in the similar way as described for SPWM. The instantaneous phase voltage, line voltage, switching pattern is similar to that of SPWM as shown in table 3. Hybrid controllers are suitable for higher PWM frequency. In this work the PWM frequency is limited to 10.8Khz so general purpose microcontroller is used for PWM generation. Pre-calculated duty values for all states in one cycle of phase voltage are generated for fixed modulation index and used. Space vector PWM modulation technique is equivalent to the third harmonic injected sinusoidal PWM modulation technique. PWM duty values are generated with respect to 16% third harmonic injected sinusoidal signal.

4 HARDWARE RESULTS:

The three phase inverter system is designed and implemented to verify results. The detailed hardware configuration and its performance is analysed in this sections. The microcontroller program code consists modules for LCD, input/output voltage setting, duty cycle setting, code for 120^0 conduction, 180^0 conduction, SPWM and harmonic injected PWM etc. The controller program memory is fully utillized. The program code size after compiling is around 30kb. This makes testing of three phase inverter in all four modes easier. Test is carried out for the three phase star connected induction motor load connected across the inverter three phase output ac lines.

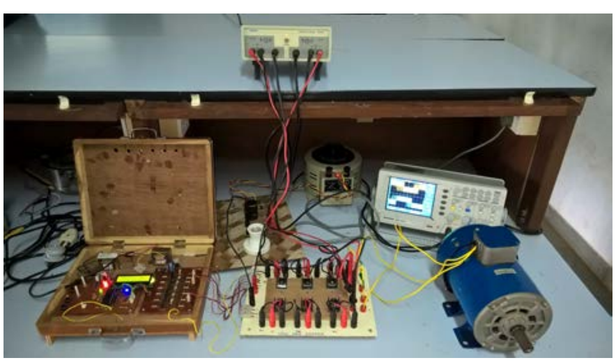

Fig. 8 Experimental setup of 3PIM drive.

Fig. 8 shows the experimental setup of three phase inverter with motor load. The control circuit , low power dc supply and driver cicuit, the main inverter bridge circuit and lamp load are implemented on saperate board. DSO is used to observe voltage and current waveforms at various points.

4.1 Hardware Results for 120^0 conduction

The practical results for phase voltage and line voltage with α=1 and α = 0.65 in 120^0 conduction mode is shown in the fig. 9 and fig. 10 respectively. This is single pulse modulation technique. Test results are taken for 350V input dc voltage. By varyig duty cycle the output voltage can be varied from zero to maximum value. For α=1 the output phase voltage =143V and line voltage = 250V which matches with theorotical results.

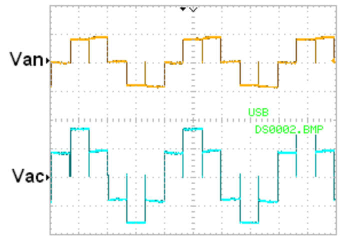

Fig. 9 Waveforms for α = 1

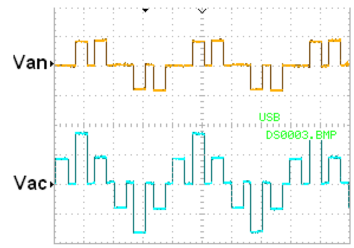

Fig. 10 Waveforms for α = 0.65

During zero state all switches remains in off state resulting in zero output voltage. As discussed earlier zero state time is equal to the switching state period (3.33ms) minus active state time of switch combination.

4.2 Hardware Results for 180^0 conduction

The practical results for phase voltage and line voltage with α=1 and α = 0.6 in 180^0 conduction mode is shown in the fig. 11 and fig. 12 respectively. This is also single pulse modulation technique. Test results are taken for 350V input dc voltage. By varyig duty cycle the output voltage can be varied from 0 to maximum value. For α=1 the output phase voltage is equal to 165V and line voltage is equal to 285V which matches with theorotical results.

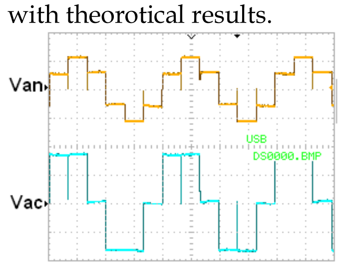

Fig. 4 Waveforms for α = 1

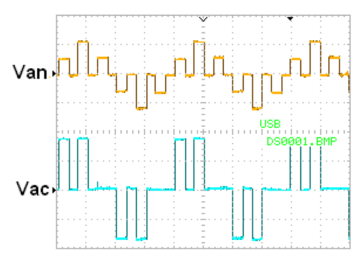

Fig. 52 Waveforms for α = 0.6

The motor current waveforms for 180^0 and 120^0 conduction mode are shown in the following figure 13. It shows that the line current waveforms for motor load is distorted and not perfect sine wave, due to large harmonic content. This shows that in single pulse modulation produce large harmonic distortion in output current.

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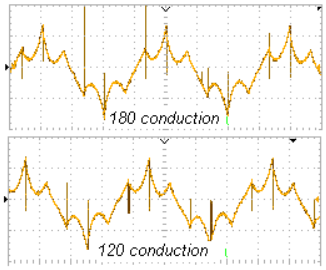

Fig. 6 Line Current Waveforms

4.3 Hardware Results for SPWM and Harmonic injected PWM Inverter

Following fig. 14 shows the phase voltage and line voltage output waveform for traditional PWM mode of operation. As expected the phase voltage waveform is six step waveform. The input dc supply is 350V, the modulation index is fixed at 0.95, so the output ac phase voltage is given by

$$V_{ac} = M.\frac{Vdc}{2\sqrt{2}} = 118\text{V} \qquad (1)$$

The theoretical and experimental results are tabulated in the table 4. Input DC voltage = 350V.

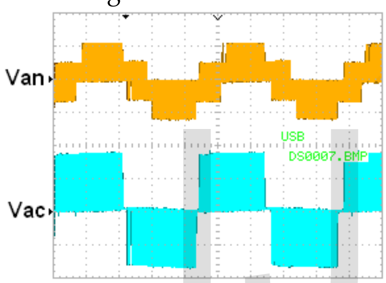

Fig. 7 Phase Voltage and line voltage

Table 4 Observation Table

Sr	Parameter	Theoretical	Practical
1	DC link Voltage(V)	350	350
2	Line Voltage (V)	202	199
3	Phase voltage(V)	118	115

The test rsults for phase voltage and line to line voltage waveforms are shown in the fig. 14, fig. 15, and fig. 16. The output line to line voltage is found to be about 199V practically while the theoretical value is 202 for Vdc = 350V. The output phase voltage is found to be about 115V practically, while the theoretical value is 118V for Vdc = 350V. Thus experimental results are consistant with this theoretical result for traditional inverter.

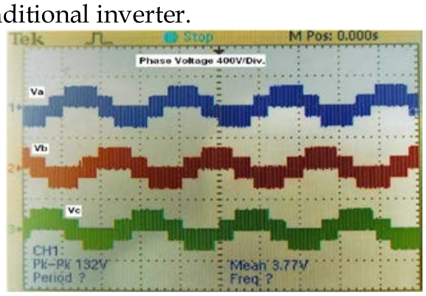

Fig. 8 Phase Voltage waveforms

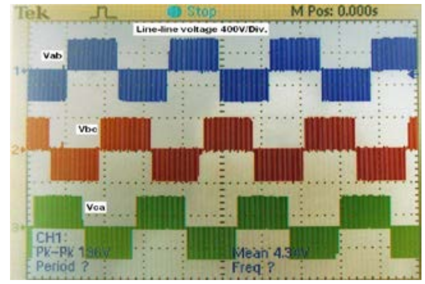

Fig. 9 Line to Line voltage waveforms

The theoretical and practical results are for harmonic injected PWM method is tablated in the following table 5. Input DC voltage is set to 350V.

Table 5 Observation Table

Sr.	Parameter	Theorotical	Practical
1	DC link Voltage (V)	350	350
2	Line to Line Voltage(V)	234	229
3	Output phase voltage(V)	135	129

Practically it is verified that for same modulation index the harmonic injected PWM method gives about 15% more output voltage than that of SPWM.

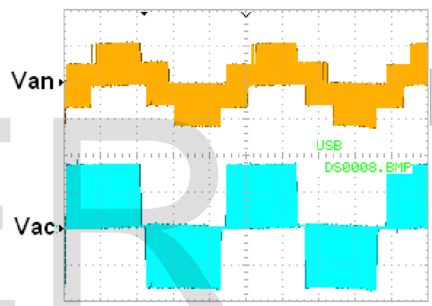

Fig. 10 Voltage waveforms in SPWM mode.

The three phase output phse voltage and line voltage waveforms for SVPWM method are same as SPWM method as shown in the fig. 15 and fig. 16. The three phase output voltage waveform consists of six step as in case of SPWM inverter. The phase voltage is found to be 129V practially, while theoretical value is 135V. The line to line voltage observed is 229V, while theoretical value is 234Volt. As shown line to line voltage is square waveform with PWM variations. The peak to peak value of these pulses varies between ±350V. The three phase load current waveforms for motor load is shown in the fig. 18. To observe current waveforms 1Ω/3W resistor is connected in series with each of three phase stator windings. The voltage drop across these resistors is observed using differential module and DSO. The voltage drop across each of these resistors is equal to current flowing through associated stator winding.

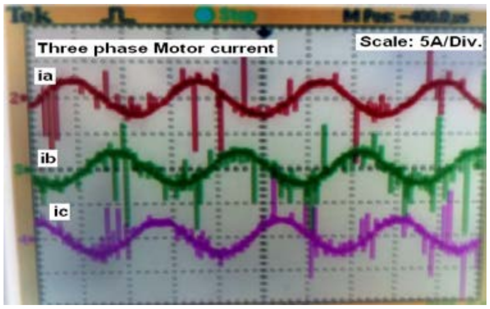

Fig. 11 Line current for motor load

Table 6 Relative Performance of 3Φ inverter in various PWM modulation techniques

Peformance Parameters	Single pulse modulation		Multiple pulse modulation	
	120^0 conduction mode	180^0 conduction mode	SPWM	SVPWM
Switching states	2	2	3	4
Swtching losses	low	low	higher	highest
THD	Highest	Higher	Low	Lowest
Dominamt Harmonics	Lower order $3f_m$, $5f_m$, $7f_m$	Lower order $3f_m$, $5f_m$	High freq. f_c	High freq. f_c
Efficiency	High	Higher	Medium	High

4 CONCLUSION:

In this work, described the hardware implementation, analyzed the circuit, and demonstrated the concept theoretically and practically. The third harmonic injected PWM control method produces around 16% higher output voltage as compared to SPWM mode. It allows over modulation where modulation index can be increased up to 1.154. The relative performance of four methods is tabulated in the table 6. All PWM methods are implemented using PIC microcontroller 18f452 general purpose microcontroller. Run time speed control is easily achieved using ADC module and timer combination in 120^0 and 180^0 conduction mode due to comparatively large switching cycle period (3.33ms). So closed loop control is possible in 120^0 and 180^0 conduction mode using PIC microcontroller. Synchronized three phase SPWM and harmonic injected PWM signals can be generated using its timer (8 bit) for fixed modulation index and frequency (10.8Khz) using look up table method. Synchronized three phase PWM signal thus generated can be used to operate induction motor. Closed loop control is also possible in SPWM and SVPWM mode using ADC module but at lower switching frequency. The program time overheads puts limits on maximum PWM frequency that microcontroller can generate. Practically it is found that with 20MHz crystal, maximum three phase PWM frequency is limited to <12Khz in PIC18fxx2 microcontroller. Hardware results are compared in all PWM mode, are consistent with theoretical results. Thus developed system is very useful in practical labs to demonstrate and verify results of various PWM control methods used in 3Φ inverter, single phase full bridge inerter and even four quadrant chopper drive. Single phase full bridge inverter and four quadrant chopper drive requires four switches of 3Φ Inverter Bridge.

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