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XMEGA-Based Implementation of Four-Switch, Three-Phase Voltage Source Inverter-Fed Induction Motor Drive

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ABSTRACT

Induction motors offer many advantages tools, and therefore are becoming very popular industrially and commercially. This paper presents the implementation of Xmega microcontroller based PWM inverter controlled of four-switch three phase voltage source inverter (FSTPI) fed induction motor drive. The reduction of the number of power switches from six to four improves the cost effectiveness, volume-compactness and reliability of the three phase inverters in addition to less complexity of control algorithms and reduced interface circuits. Simulation and experimental work are carried out and results presented to demonstrate the feasibility of the proposed approach. Simulation is carried out using SIMULINK and in experimental work, a prototype model is built to verify the simulation results. XMEGA microcontroller (XMEGA64A3) is used to generate the PWM pulses with a new algorithm for FSTPI to drive a 5 hp, 3-phase induction motor. Experimental and simulation results show that the proposed drive system provides a fast speed response and good disturbance rejection capability.

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1. INTRODUCTION

Over the years induction motor (IM) has been utilized as a workhorse in the industry due to its easy construction, high robustness, and generally satisfactory efficiency [1]. With the invent of high speed power semiconductor devices three-phase inverters play the key role for variable speed ac motor drives. Traditionally, 6-switch, 3-phase inverters have been widely utilized for variable speed IM drives. This involves the losses of the six switches as well as the complexity of the control algorithms and interface circuits to generate six PWM logic signals. In the past, researchers mainly concentrated on the development of the efficient control algorithms for high performance variable speed IM drives [2]-[3]. However, the cost, simplicity and flexibility of the overall drive system which become some of the most important factors did not get that much attention to the researchers. That is why, despite extensive research in this area most of the Induction motors are being used for many industrial and commercial applications because of its easy built, high robustness, and good efficiency. Induction motors which contain a cage are very popular in variable-speed drives. They are simple, rugged, inexpensive and available at all power ratings. Progress in the field of power electronics and microelectronics enable the application of induction motors for high-performance drives. The speed of the induction motor can be controlled by varying its input AC voltage and frequency using an inverter.

A standard six switch three phase voltage source inverter has six switches in three legs with a pair of complementary power switches per phase. But, a reduced switch count voltage source inverter such four switch three-phase inverter uses only two legs, with four switches. The advantage of this inverter due to the use of 4 switches instead of conventional 6 switches is less switching losses, lower noise and less complexity of control algorithms and reduced interface circuits. Several articles report on FSTPI structure [4]-[8].

In recent years, with the increasing use of microcontrollers in power electronics, it becomes possible to use it to generate the pulse width modulation. The Xmega A is a family of low power, high performance and peripheral rich CMOS 8/16-bit microcontrollers based on the AVR enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the Xmega A achieves throughputs approaching 16 Million Instructions Per Second (MIPS) per MHz allowing the system designer to optimize power consumption versus processing speed [9]. The Xmega by AWeX realization of PWM provides advantages such as fast prototyping, strong hardware and software design, higher switching frequency and reduction of the computational load of the process.

2. PROPOSED CONTROL SCHEME

The block diagram of the proposed system is shown in figure 1. In the simulation and experimental work, at first the single phase half bridge rectifier converts AC power to DC. The DC power is fed to FSTPI. The FSTPI converts the DC power to controlled 3-phase AC power and then a 3-phase induction motor is driven by the FSTPI. Xmega microcontroller Xmega64a3 is used to generate the controlled PWM pulse for FSTPI. The controlled PWM pulses of microcontroller are fed to the gate of IGBTs of FSTPI through the driver circuit to drive the IM. The structure control of PWM in Xmega is very strong.

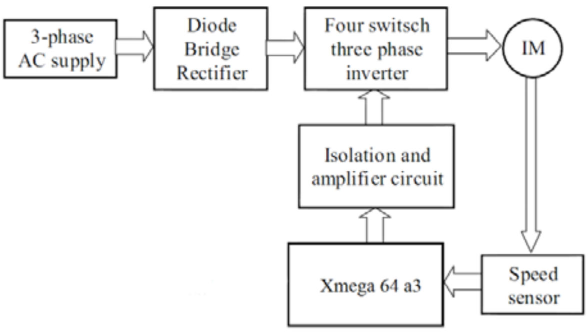


Figure 1. The block diagram of Xmega-based FSTPI induction motor drive

2.1. Basic Circuit Description

In motor control applications, open-loop control is used to control the speed of the motor by directly controlling the duty cycle of the PWM signal that directs the motor-drive circuitry. The duty cycle of the PWM signal controls the ON time of the power MOSFETs in the half bridges of the motor-drive circuit and this in turn controls the average voltage supplied across the motor windings. The power circuit of the FSTPI fed induction motor drive is shown in figure 2. The Speed Control Input unit provides the motor-speed input to the control system. This input can either be analog or digital. Depending on the speed-control input, the open-loop control system implemented in the Xmega either increases or decreases the PWM duty cycle, which in turn increases or decreases the average voltage or current, applied to the motor via the motor-drive circuitry and controls the motor speed accordingly. The power inverter has 4 IGBT switches, S_1, S_2, S_3 and S_4 and two capacitor C_1 and C_2 as DC link. The switches are controlled in order to generate an AC output from the DC input. The two phases ‘a’ and ‘b’ are connected to two legs of the inverter, while the third phase ‘c’ is connected to the center point of split DC link. The capacitances C_1 and C_2 are the same. V_{c1} and V_{c2} are the voltages across the DC link ($V_c = V_{dc}/2$). The four power switches can be assumed to be denoted by binary variables S_1 to S_4. Binary ‘1’ corresponds to an ON state while binary ‘0’ corresponds to an OFF state. The states of the upper switches (S_1, S_2) and lower switches (S_3, S_4) of a leg are complementary that means $S_3 = 1 - S_1$ and $S_4 = 1 - S_2$. Considering a 3 phase Y-connected induction motor, the terminal voltages V_{as}, V_{bs} and V_{cs} can be expressed as the function of the states of upper switches as follows:

$$V_{as} = \frac{V_C}{3}(4S_1 - 2S_2 - 1) \quad (1)$$

$$V_{bs} = \frac{V_C}{3}(-2S_1 + 4S_2 - 1) \quad (2)$$

$$V_{cs} = \frac{V_C}{3}(-2S_1 - 2S_2 + 2) \quad (3)$$

where V_c is the voltage across the DC link capacitors, and S_1 and S_2 are taken as the switching functions of upper switches. The matrix form of above equations can be written as:

$$\begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} = \frac{V_c}{3}\begin{bmatrix} 4 & -2 \\ -2 & 4 \\ -2 & -2 \end{bmatrix}\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} + \frac{V_c}{3}\begin{bmatrix} -1 \\ -1 \\ 2 \end{bmatrix} \quad (4)$$

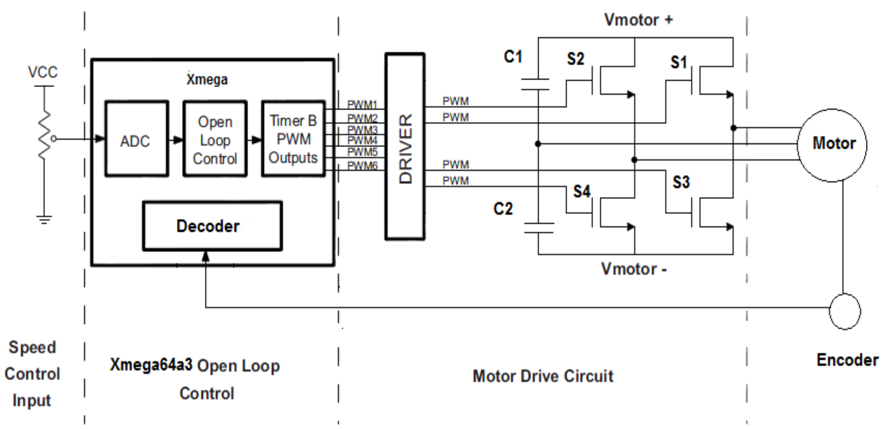


Figure 2. FSTPI with induction motor and drive

Table 1 shows the different modes of operation and the corresponding output phase voltages of the inverter.

Table 1. Operation modes of FSTPI and the output voltages

Output voltage			Switching states	
Vcs	Vbs	Vas	S2	S1
$2V_c/3$	$-V_c/3$	$-V_c/3$	0	0
0	V_c	$-V_c$	1	0
0	$-V_c$	V_c	0	1
$-2V_c/3$	$V_c/3$	$V_c/3$	1	1

2.2. PWM generation in Xmega microcontroller

Some Timer/Counters on the Xmega have extension modules that are useful for applications such as motor and power control applications. The Advanced Waveform eXtension (AWeX) is a collection of Timer/Counter extensions that are typically used in motor and power control applications. If the AWeX extension is used, the PWM outputs of the Timer/Counter module are routed through the AWeX module that controls the port pins. Figure 3 shows an overview of the AWeX module with its three sub-functions: Dead-time Insertion (DTI), Pattern generation and Fault protection.

In many applications, such as motor control, PWM is used to generate waveforms using a half-bridge configuration similar to the one shown in figure 4. If the high- and low-side switches are fed with inverted PWM waveforms (PWM_H and PWM_L), the average output voltage, V_{OUT}, will be proportional to the duty cycle of the PWM_H signal [6].

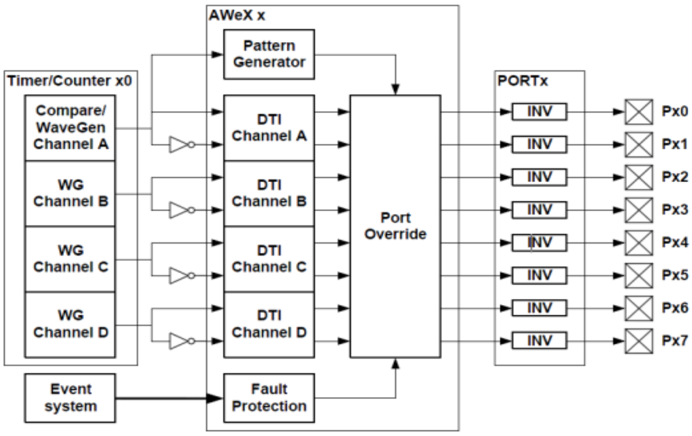


Figure 3. AWeX module overview

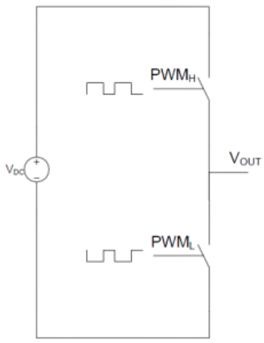


Figure 4. Typical half-bridge setup

A half-bridge, like the one in figure 4, is typically realized using MOSFETs or IGBTs. These devices are not capable of turning on/off instantaneously. There is always a small rise/fall time on the output. If the signal applied to the low side switch is just an inverted version of the signal applied to the high side, there will be a small period during the switching where both the high- and low-side switches are conducting, leading to a short-circuit between positive supply and ground for a short period. This is usually known as shoot-through, and should obviously be avoided. The usual solution to avoid shoot-through is to insert a small dead-time around the switching instant. When the low side is switched off, the high-side is not switched on until after the dead-time has passed. This is called dead-time insertion.

The Dead-time insertion extension handles dead-time insertion automatically, ensuring that shoot-through cannot happen as a result of a software glitch. The dead-time for high-side and low-side can be set individually through the DTHS and DTLS registers respectively. As a shortcut, DTHS and DTLS can be set to the same value by writing to the DTBOTH register. The dead-time value is given in main system clock cycles. The allowable range for the dead-time is thus 0-255 main system clock cycles.

3. SIMULATION WORK AND RESULTS

Digital computer simulation model using SIMULINK has been developed to test the proposed FSTPI fed IM drive block as shown in figure 5. Simulation circuit diagram of the system is shown in figure 6. The FSTPI fed drive system consists of a three-phase diode bridge rectifier, a split capacitor, four switch three phase inverter and 3-phase squirrel cage induction motor. The input three-phase supply voltage is 400 V at 50 Hz and the rated value of three-phase induction motor is 5 hp, 400 V, 50 Hz, 1500 rpm.

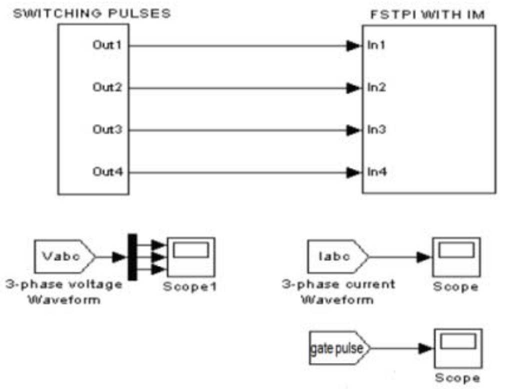


Figure 5. The Simulink block diagram of FSTPI fed drive system

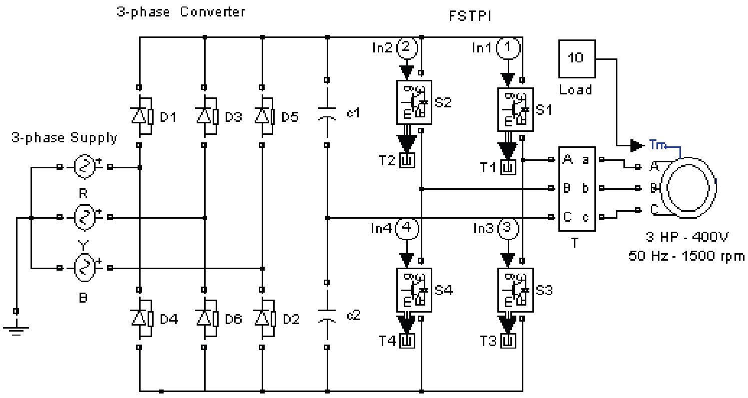
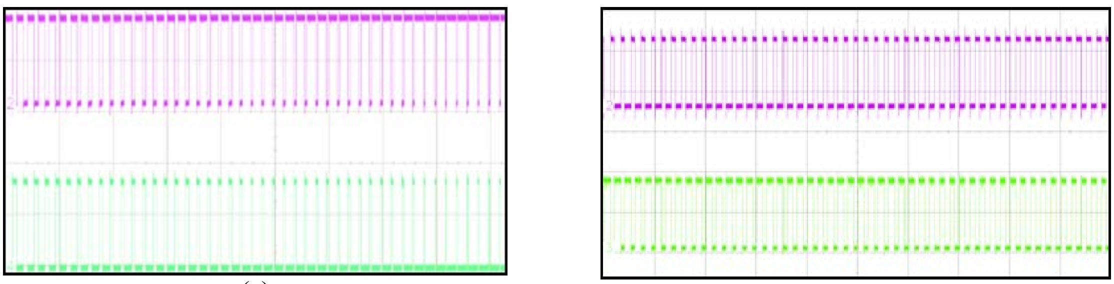


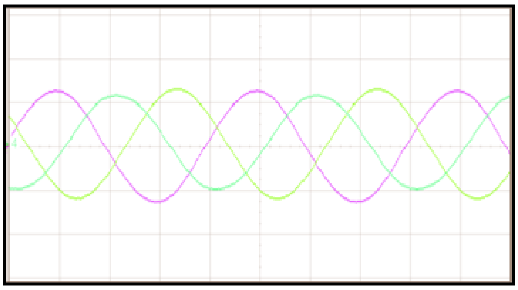
Figure 6. The simulation circuit diagram of FSTPI fed IM drive system

The output waveforms such as SPWM pulses for FSTPI, three phase currents and three phase line voltages of FSTPI with induction motor are shown using digital storage oscilloscope. The sinusoidal PWM pulses for all switches of FSTPI are shown in figure 7a and figure 7b. These SPWM pulses are obtained by comparing sinusoidal waveform and triangular carrier waveform. The switching frequency is selected 15 kHz. The output current waveform of FSTPI with induction motor has been shown in figure 8a. It is observed that a balanced 3-phase output current waveform is obtained. Figure 8b shows the line output voltage waveform of the FSTPI. Figure 9 shows the output voltage V_{bc} (between phase 'b' and 'c') and V_{ca} (between phase 'c' and 'a') of FSTPI.



(a) (b)

Figure 7. SPWM pulses for (a) switches S_1 and S_3, (b) switches S_2 and S_4


(a)

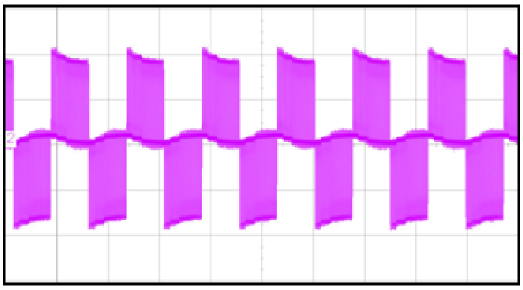

(b)

Figure 8. (a) Three phase current waveforms of FSTPI, (b) FSTPI phase to phase output voltage V_{ab}

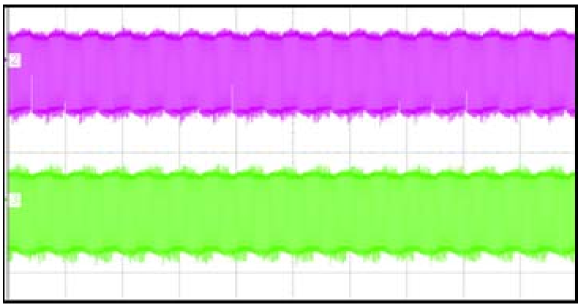
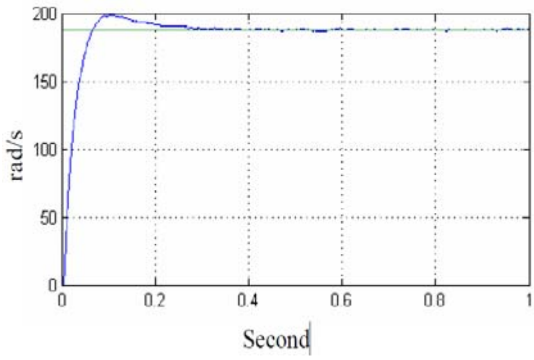
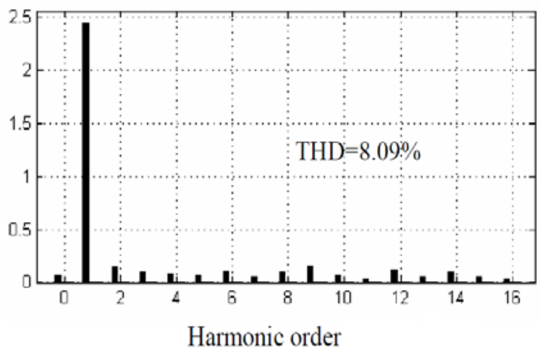


Figure 9. FSTPI phase to phase output voltage V_{bc} and V_{ca}

Figure 10a shows the simulation starting responses of the IM drive fed from the proposed 4-switch, 3-phase inverter. It shows that the motor speed follows the command speed accurately without steady-state error. These currents are verified by conventional 6-swicth, 3-phase inverter response shown in figure 11. The harmonic spectrum of a phase current i_a for the proposed inverter is shown in figure 10b. The total harmonic distortion (THD) of i_a is found 8.09%, Whereas the THD of i_a for the conventional inverter is found 10.5% as shown in figure 11.



(a)



(b)

Figure 10. Simulation starting responses of the proposed inverter based drive at rated speed and rated load conditions: (a) speed and (b) harmonic spectrum of current ia.

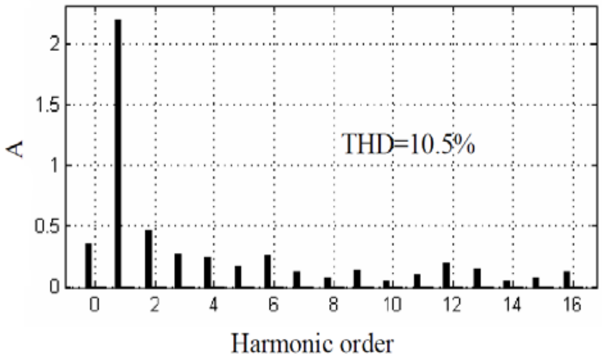


Figure 11. Simulation responses of the conventional 6-switch, 3-phase inverter based drive at rated speed and rated load conditions steady state 3-phase currents.

4. EXPERIMENTAL WORK AND RESULTS

4.1. Software Implementation

In the experimental work, source code is written in the C language using Codevision AVR inbuilt text editor. The code was tested using on-chip JTAG debugger simulator. Finally the microcontroller is programmed via JTAG connection. Figure 12 describes the flow chart used to generate the modified PWM with AWeX signals implemented in the Xmega microcontroller.

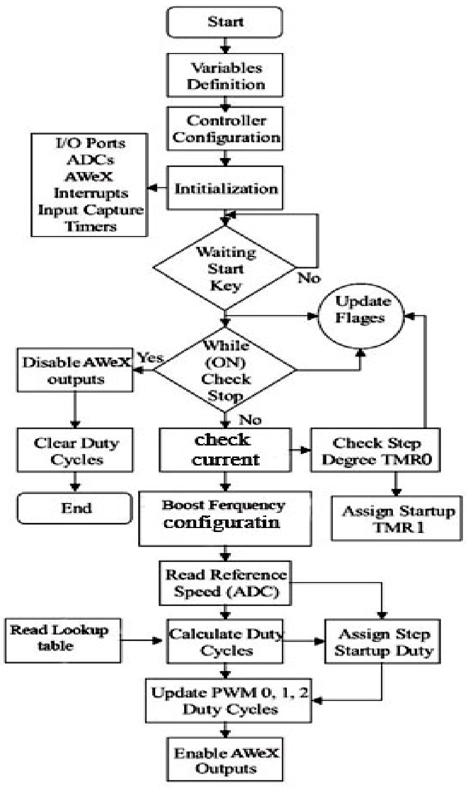


Figure 12. Flowchart of AWeX Controller

4.2. System Hardware Design

The complete prototype of the experimental setup is shown in Figure 13. The details of the components used in this experiment are given in Table 2. The potential transformer is used to provide the power to Xmega microcontroller board and driver circuit board. A single phase diode bridge rectifier and filter circuit is used to convert AC to DC. Four IGBTs and 2-split capacitors are used to form FSTPI. The output of FSTPI is connected to the 5 hp 3-phase Induction Motor.

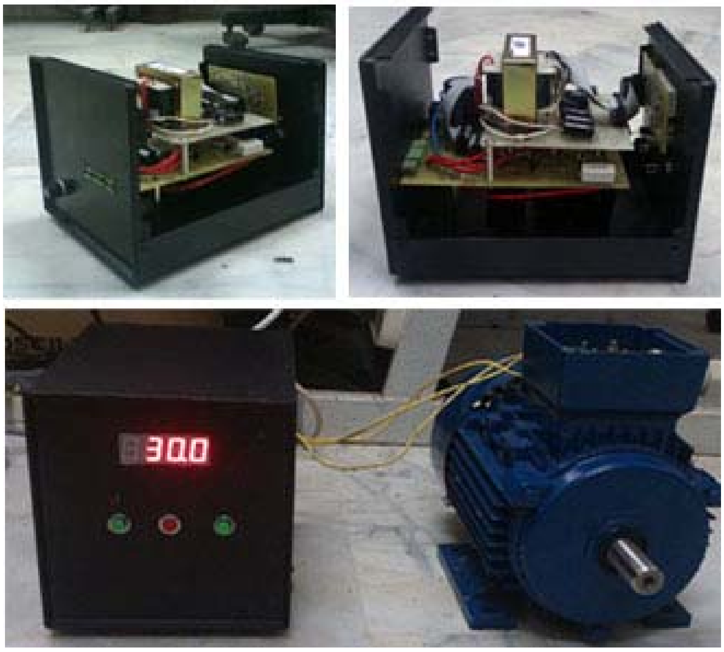


Figure 13. Complete hardware setup of Xmega microcontroller based FSTPI fed IM Drive.

Table 2. Detail Hardware components and ratings

Component	Rating
Xmega64a3	• High-Performance 8/16-Bit CPU On-Chip Memory • Event System • System Clock and Clock options • TC - 16-bit Timer/Counter • AWeX - Advanced Waveform Extension • Memory Programming
HCPL-0314	•Isolation & IGBT Driver Component
Inverter module	•IGBT 600 V, 32A with snubber circuit •Full bridge diode converter •Capacitor 2000 μF 450v •Isolation Power Supply
Induction Motor	5 Hp,3-phase, 50 Hz, 1500 rpm

5. EXPERIMENTAL RESULTS

The experimental results obtained are shown in the following figures. Figure 15 shows the controlled output PWM pulses of MCU for switches S_1 and S_2, with adjustable pulse width and frequency. Pulses of S_3 and S_4 are the similar but the reverse of S_1 and S_2. The output current i_a of the single phase system fed to an induction motor is shown in Figure 14.

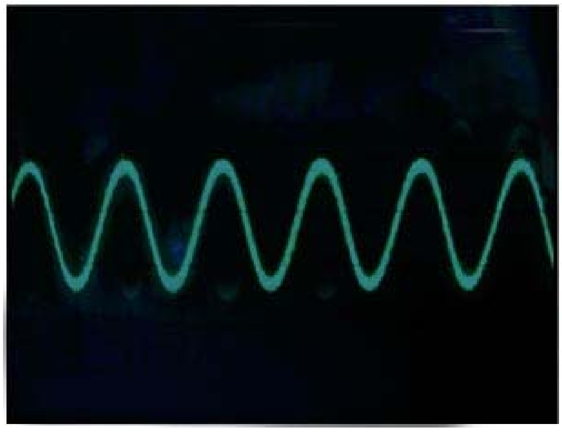


Figure 14. Output current i_a of FSTPI with IM.

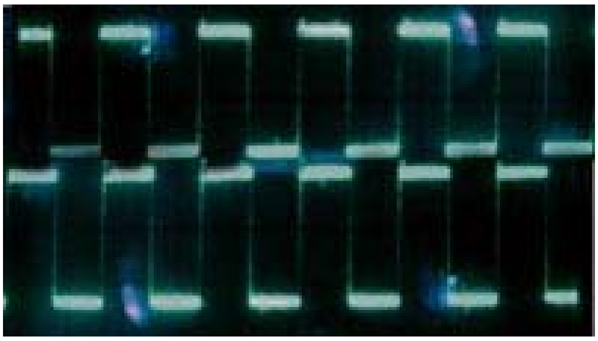


Figure 15. Pulses to switch S_1 and S_2

6. CONCLUSION

A cost effective FSTP inverter fed IM drive has been developed, simulated and successfully implemented in real-time using Xmega microcontroller for a prototype 5 hp motor. The proposed control approach reduces the cost of the inverter, the switching losses, and the complexity of the control algorithms and interface circuits to generate 6 PWM logic signals. A performance comparison of the proposed FSTP inverter fed drive with a conventional SSTP inverter fed drive is also made in terms of total harmonic distortion (THD) of the stator current and speed response. The proposed FSTP inverter fed IM drive is found acceptable considering its cost reduction and other advantageous features. It was shown that it is economic to run light-load system, since it uses 4 switches instead of 6 and can be easily controlled by a low-cost microcontroller, resulting in a cost effective high performance/cost drive unit.

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