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MICROCONTROLLER BASED 120⁰AND 180⁰CONDUCTION MODES OF THREE-PHASE INVERTER FOR PHOTOVOLTAIC GENERATION

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ABSTRACT
In this paper, a prototype design and implementation of the microcontroller based three-phase six switches square wave inverters for photovoltaic generation is proposed. The inverter is employed into 120^0 and 180^0 conduction modes respectively for three-phase induction motor.The system is built in the small-scale prototype and tested by performing the simulation in the PSIM. The results indicate that the proposed method is very effective and feasible to be implemented on fundamental frequency switching.

Keywords: conduction mode, microcontroller, three-phase inverter.

INTRODUCTION
The use of fossil fuels has resulted in the problems of global climate change which seriously damages the environment. The use of solar energy and wind energy can alleviate the problems of global climate change, the cost of both solar and wind energies can compete with the fossil fuels in the near future. Solar energy has gained a lot of attentions due to its popularity to solve many problems in electrical field and it is also well known as one of problem solver that eco-friendly. Photovoltaics (PV) and Concentrated Solar Power (CSP) are the implementation of the present technology that utilize the solar energy to generate electricity. In early 2014, the total capacity of solar energy that has been generated is over 150 GW [1].The cost reduction to build up the PV panel has become an alternative way to produce the clean energy generation in the world. Moreover, PV can be integrated very easily into existing power converters and it is also buildable from small until very large sizes [2]. The International Energy Agency (IEA) estimates that solar photovoltaic (PV) power generation will contribute to supply the electricity up to 16% from the total of the world's electricity where 20% of the total PV capacity is obtained from residential installations in 2020.

An inverter is required to convert the PV's output which is from DC to AC power because most loads in the customer side consume the AC power. There are various types of inverters that available and can be implemented in different aspects. Practically, single-phase and three-phase inverters are most commonly used.

The implementations of inverter are depending on the user requirement and request whether it will be applied for the industrial applications, transportations, or home

are more efficient and cost-effective to be implemented to control more digital devices compared to a design that uses a separate microprocessor, memory, and input/output devices, [11].

A system that uses microcontroller offers substantial advancement as an internal and external control. They can control most of the internal devices in a typical circuit board. Moreover, most of the chips also

appliances. Usually, single-phase and three-phase inverters are most commonly used. In industrial application, there are several types of inverters can be used such as Uninterruptible Power Supplies (UPS), Flexible AC Transmission System (FACTS) devices, Variable Frequency Drives (VFD), Active Power Filters, High Voltage Direct Current (HVDC) transmission system, etc. [3]. In most circumstances, three-phase inverters have better performances rather than single-phase inverter.

The gating signals in an inverter are required to produce output voltage. The frequency of gating signal for power switching inverter can be low and high respectively. The high frequency switching is implemented with Pulse width modulation for controllable and sophisticate inverters system whereas the low frequency switching is engaged to simple system.

Many researchers have been reported regarding to implementation of inverter for low frequency switching [4-107]. The inverters conduct 120^0, 150^0 and 180^0 for fundamental frequency. Although the same topology and different conduction mode, the inverter generate different waveform.

The analog and digital circuit can be employed to generate the gating signal for inverter. Commonly, the analog circuit for gating signal inverter comprises an IC (integrated circuit) that embedded to generate sinusoidal, square or triangle waveforms. Meanwhile, the digital circuit is engaged with a processor (microprocessor or microcontroller)

The microcontroller can be interpreted as a small computer on a single integrated circuit that contains one or more CPUs (processor cores) along with memory and programmable input/output peripherals. Microcontrollers have built-in interfaces that can be controlled by the microcontroller [11].

This paper recounts some theoretical, analytical and experimental issues of three-phasesix switches square wave inverter for PV system application with 120^0 and 180^0 conduction modes. The algorithm of all switching angles for power switching are embedded in a low cost processor ATMega 8535.

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THREE-PHASE INVERTER

Inverter is a device that has a function to convert a DC input voltage to an AC output corresponding to desired frequency and magnitude. Depending on the type of the supply source and the related topology of the power circuit, it is classified as Voltage Source Inverter (VSI) and Current Source Inverter (CSI). In VSI topology, voltage waveform is being the AC output that want to be controlled. Meanwhile, in CSI topologies, the one that want to be controlled is a current waveform. The standard three-phase inverter shown in Figure 1 consists of six main power switches of which depends on modulation scheme and six freewheeling diodes. Several types of power switches can be used such as IGBT, MOSFET, GTO etc. It depends on the application.

Three phase inverter in the figure below has three arms which have angle differences by 120° toward each other to generate a three-phase AC supply. Each switch has a ratio up to 50% and switching process is always occurred after every T/6 from the total time (by the angle interval of 60°). The switches S_1 and S_4 are complemented each other and operated interchangeably. The same condition is also happened in the switches S_2 and S_5, and switches S_3 and S_6.

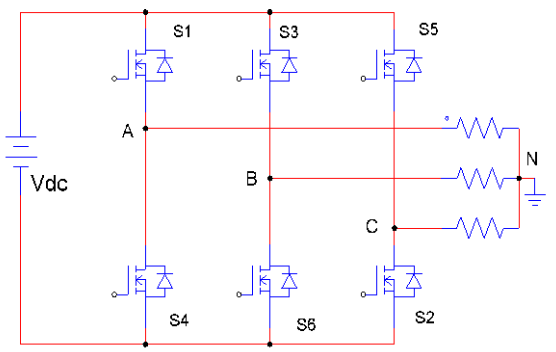

Figure-1. Three-phase inverter.

In three - phase inverter, all switches have two types of conduction mode. In the first mode, each switch conducts the signal with the interval of 180^0. Otherwise, in the second mode, the signal is conducted in 120^0. But when both modes are applied at the same time, the signal will be removed at interval of 60^0 from the output voltage waveform. Either 120^0or 180^0mode necessitates a six step bridge inverter.

Three-phase 120^0 mode of conduction

This conduction mode requires each power switch to conduct in the state of 120°. It is most appropriate to be applied in the kind of load with delta connection sinceit able to generate a six-step type of waveform in each phase. Each switch will conduct for 120^0interval or each of power switch turns on for 1/3 period and for each $60^0$of degree interval two switches are on and four switches are off. The switching states for 120^0 are shown in Table-1.

In the Figure-1, the terminal A and B of the load are connected to the positive and negative side of the source respectively. While the terminal C is in a condition called floating state.

By using the Fourier analysis, the output voltage can be extracted from the following equations [9].

$$V_{0,a,120^0} = \sum_{n=13,..}^{\infty} \frac{2V_d}{\sqrt{3}n\pi} \cos\frac{n\pi}{6} \sin n\left(\omega t + \frac{\pi}{6}\right) \quad (1)$$

Then, RMS and THD values of output voltage can be calculated as follow:

$$V_{0,a,120^0} = 0{,}41 V_i \quad (2)$$

$$THD_{V_0,120^0} = 31\% \quad (3)$$

Table-1. Switching states for 120^0 mode conduction.

State	Switching states					
	S_1	**S_2**	**S_3**	**S_4**	**S_5**	**S_6**
1.	1	0	0	0	0	1
2.	1	1	0	0	0	0
3.	0	1	1	0	0	0
4.	0	0	1	1	0	0
5.	0	0	0	1	1	0
6.	0	0	0	0	1	1

1 = on and 0 = off

Three-phase inverter 180^0 mode conduction

In the conducting mode of 180^0, each switch is conducting in the degree of 180^0. During the process, three switches are on and the rest of switches are off at any instant of time in every interval of 60^0, then three switches will conduct simultaneously, two of which are from the same group (upper three or lower three) and remaining one from the other group. After every 60^0 or $\pi/3$ radians, one of the conducting switches is turned off and some other switches will start conducting. The conduction sequence can be written as follows $S_6S_1S_2$, $S_1S_2S_3$,$S_2S_3S_4$, $S_3S_4S_5$, $S_4S_5S_6$, and $S_5S_6S_1$. By considering one switching sequence $S_1S_2S_3$, S_1S_3 as upper group and S_2 as lower group. S_1, S_2 and S_3 operated delay at $\omega t = 0^0$, $\omega t = 120^0$ and $\omega t = 60^0$, respectively.

Each switches in the upper group i.e. S_1, S_3, and $S_5$are conducting with interval of 120°. It indicates that if $S_1$is operated at $\omega t = 0^0$, then S_3 and S_5must be operated at $\omega t = 120^0$ and $\omega t = 240^0$ respectively. The similar condition is also happened in the lower group of switches. Table-2 shows the result of switching states for six switches and the value of V_{ab}, V_{bc} and V_{ca} are calculated by using the equation (4).

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Table-2. Switching states for 180^0 mode conduction.

State	Switching states					
	S_1	S_2	S_3	S_4	S_5	S_6
1.	1	0	0	0	1	1
2.	1	1	0	0	0	1
3.	1	1	1	0	0	0
4.	0	1	1	1	0	0
5.	0	0	1	1	1	0
6.	0	0	0	1	1	1

Analysis of output voltage to Fourier series is as followed [9].

$$V_{0,a,180^0} = \sum_{n=13,5..}^{\infty} \frac{4V_d}{\sqrt{3}n\pi} \cos\frac{n\pi}{6} \sin n\omega t \quad (4)$$

Then, RMS and THD values of output voltage can be calculated as follow:

$$V_{0,a,180^0} = 0{,}48V_i \quad (5)$$

$$THD_{V_0,180^0} = 31\% \quad (6)$$

PROPOSED SCHEME

A general block diagram of the proposed scheme is illustrated in Figure-2. The whole systems consist of photovoltaic module, MPPT controller, battery, inverter and three-phase induction motor. The photovoltaic module is used to generate energy. The function of MPPT controller is to extract maximum power from photovoltaic module. The battery is used as energy storage, the inverter is employed as converter DC to AC, and the three-phase induction motor is used as load system.

The inverter is connected to gate drive circuits. The circuit is employed to isolate controlling circuit with power switching circuit. In this proposed scheme, the low cost processor ATmega8535 was used to store the switching angles in this research. The ATmega8535 is belong to one of microcontroller that produces a low-power CMOS 8-bit and constructed based on the AVR enhanced RISC architecture. ATmega8535 is operated by executing the instructions in a single clock cycle, then it produces output approaching 1 MIPS per MHz which means the system is designed to optimize the power consumption according to processing speed.

In the system, only Port A.0 to Port A.5 of port A in AT Mega 8535 is employed to generate switching signals. Meanwhile, the gating signals are generated by the ATmega8535 I/O port by assigning logic “0” or “1” according to I/O pin-out. A group of Port A.0, Port A.1, and Port A.2 are used for power switches S1, S2 and S3, while a group of Port A.3, Port A.4 and Port A.5 are used for power switches S4, S5 and S6. The oscillator clock is set 1MHz, and supply voltage of VDD = 5 V.

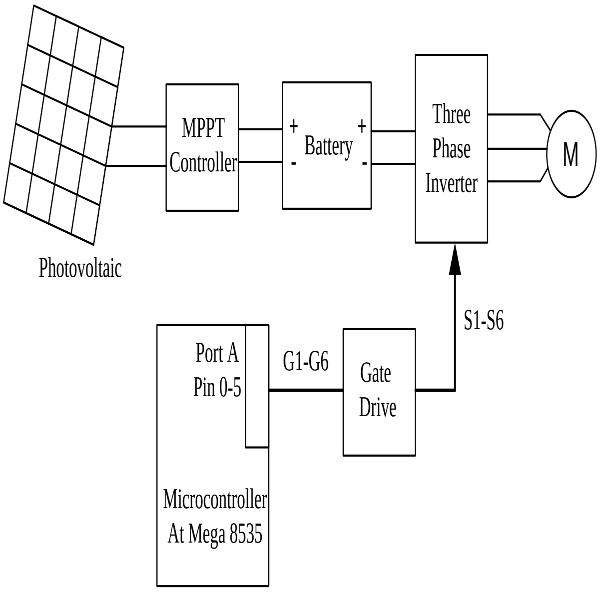

Figure-2. The proposed scheme of three-phase inverter for photovoltaic generation.

SIMULATION RESULTS

All the simulation of the proposed scheme inverter is carried out and tested by using PSIM simulation software. The inverter is simulated at 50 Hz of frequency.

Figures 3 and 4 show the result of the proposed scheme inverter simulated in120^0 conduction mode. The switching signals for S_1, S_3, and S_5 of three-phase inverter are shown in Figure-3, while the switching signals for S_2, S_4 and S_6 are shown in Figure-4. Each devices conducts simultaneously.

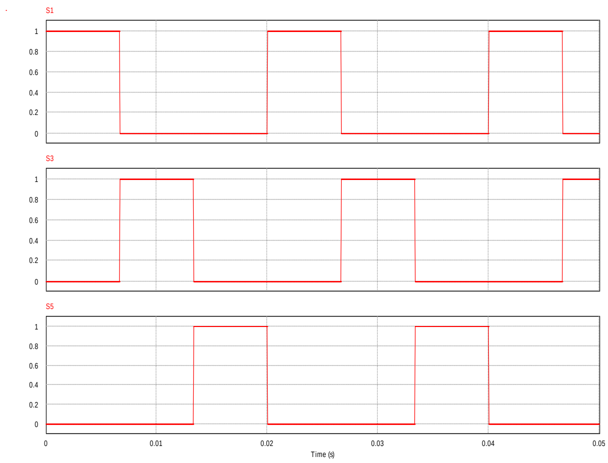

Figure-3. The switching signals of S_1, $S_3$and S_5 for 120^{0}conduction mode.

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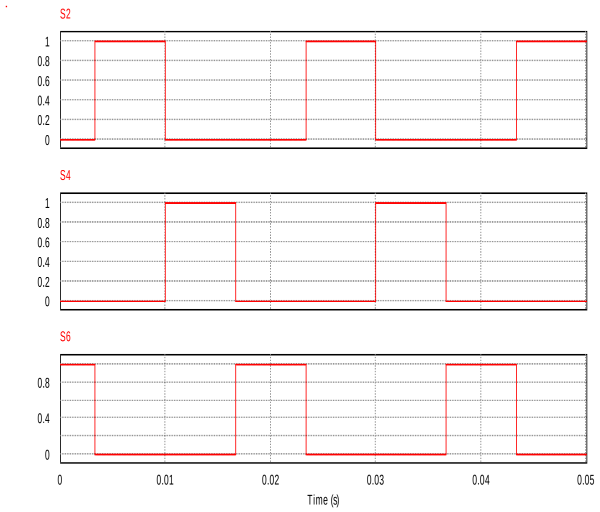

Figure-4. The switching signals of S_2, S_4 and S_6 for 120^0conduction mode.

The output of phase voltage (V_{LN}) consists of 3 levels of voltage value (Figure-5) meanwhile the line voltage (V_{LL}) consists of 4 levels (Figure-7). The results from FFT analysis for the output voltages show that there is no harmonic component existed as shown Figure-6.

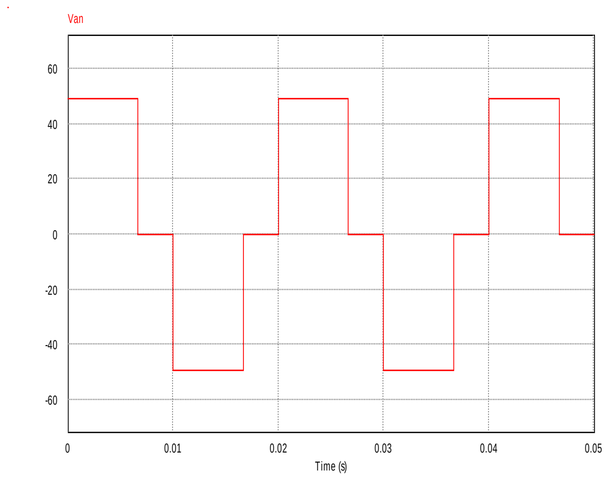

Figure-5. The output voltage waveform (V_{LN}) for 120^0 conduction mode.

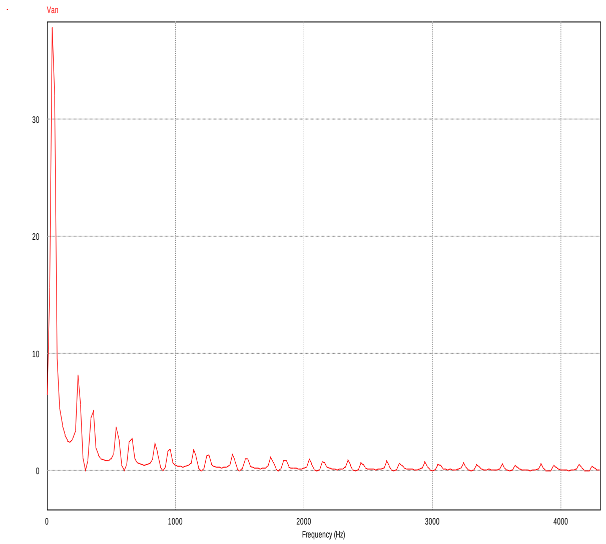

Figure-6. The FFT analysis on V_{LN} for 120^0 conduction mode.

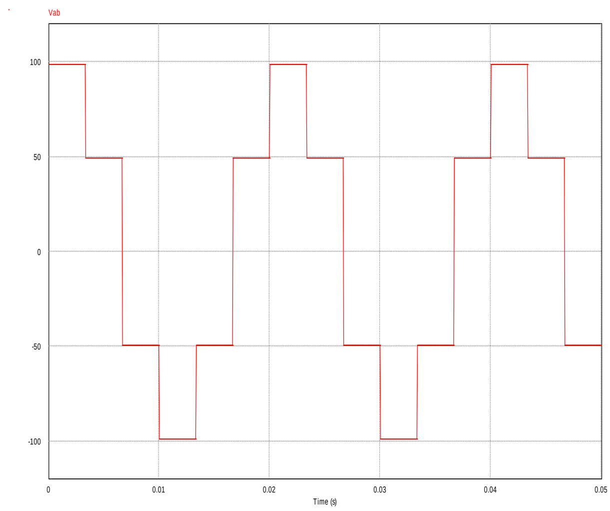

Figure-7. The output voltage waveform (V_{LL}) for 120^0 conduction mode.

Figures 8 to 12 show simulation results for 180^0 conduction mode of three-phase inverter. The gating signal for S_1, S_3 and S_5 are shown in Figure-8 while the gating signal for S_2, S_4 and S_6 are shown in Figure-9. Each power switch is turn-on in every π radian. The output voltage waveform (V_{LN}) for 180^0 conduction mode has four DC level as shown in Figure 10 and its result from the FFT analysis is shown in Figure-11 meanwhile the output voltage waveform (V_{LL}) for 180^0 conduction mode is presented in Figure-12. This waveform has three level DC.

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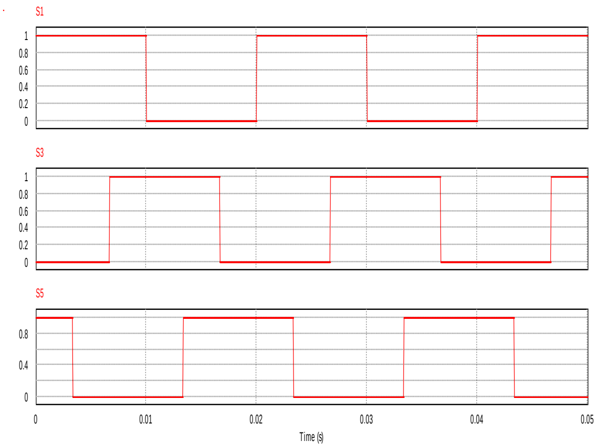

Figure-8. The switching signals of S_1, S_3 and S_5 for 180^0 conduction mode.

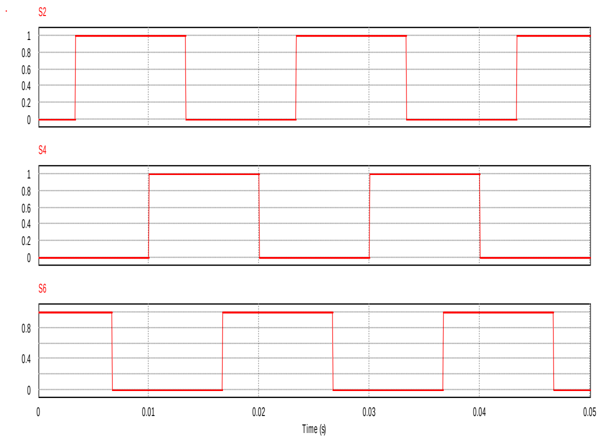

Figure-9. The switching signals of S_2, S_4 and S_6 for 180^0conduction mode.

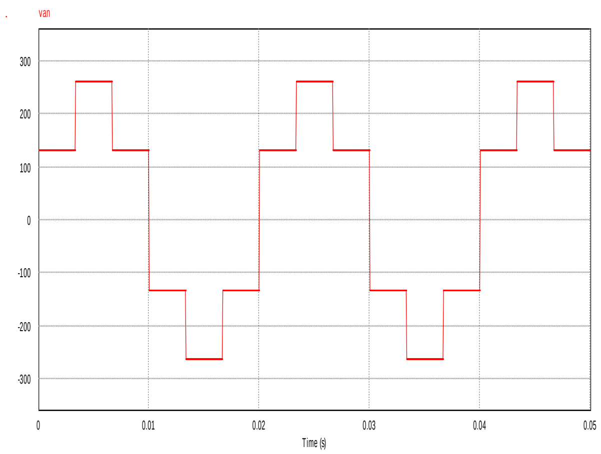

Figure-10. The output voltage waveform (V_{LN}) for 180^0 conduction mode.

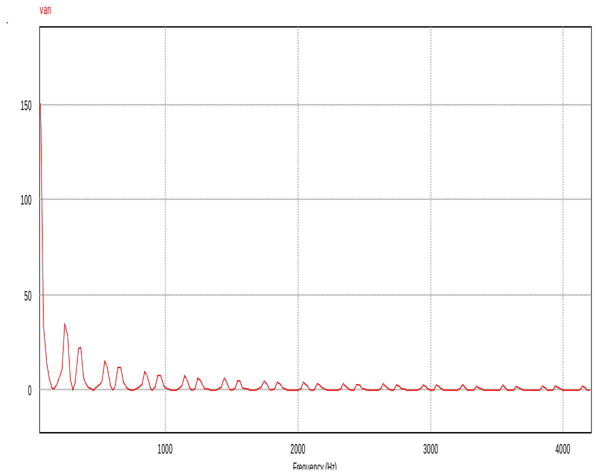

Figure-11. The FFT analysis on V_{LN} for 180^0 conduction mode.

The waveforms above show that there is no harmonic appeared in the output voltage. However, the magnitude of the fundamental component is higher than the previous conduction mode. It means that this conduction mode performs better compare to the 120^0 conduction mode.

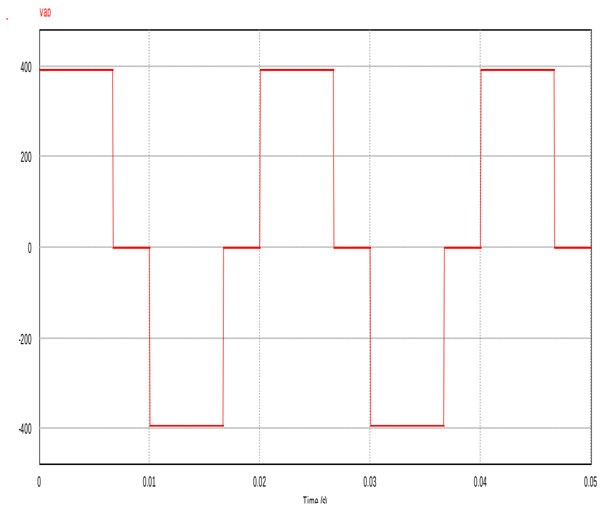

Figure-12. The output voltage waveform (V_{LL}) for 180^0 conduction mode.

EXPERIMENT RESULTS

In this experiment, the performance of three phase inverter has been analyzed as a device to convert the output of photovoltaic from DC to AC. This experiment aims to observe the capability of three-phase inverter to generate the gating signals using the microcontroller. A high voltage differential probe (PINTEK DP-25) is employed as one of tools to measure performance the inverter. With the help of A 4-channel digital oscilloscope (GwINSTEK GDS-2074A), the gating pulses as well as the three phase inverter output voltage waveforms in 120^0 and 180^0 conduction modes can be captured.

The validity of proposed scheme is testing and verifying by designing and constructing a prototype of the

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system. Ten SIEMENs SP75 modules are connected in series and parallels to produce 750 Watt of power. The switching angles for conduction mode are implied in microcontroller.

The experimental setup is shown in Figure-13. In this experiment, the photovoltaic module and battery are represented by using DC power supply. Three-phase induction motor with star-connection is engaged as load system. ATMega8535 board is employed to generate the switching signal which will be applied in the three-phase inverter.

Figure-14 shows the experiment result of the gating signals S_1, S_3 and S_5 for 120^0 conduction mode meanwhile the gating signals S_2, S_4 and S_6 are shown in Figure-15. The phase voltage output (V_{LN}) that consists of 3 voltage levels and the line voltage (V_{LL}) that consists of 4 voltage levels are shown in Figures 16 and 17, respectively.

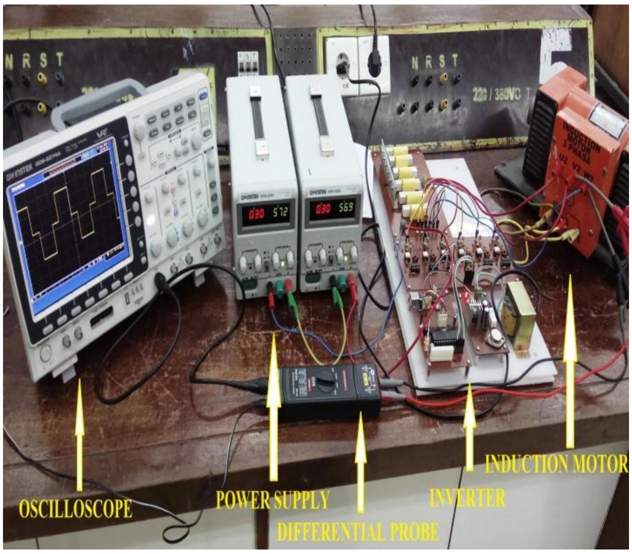

Figure-13. The experimental setup for three-phase inverter.

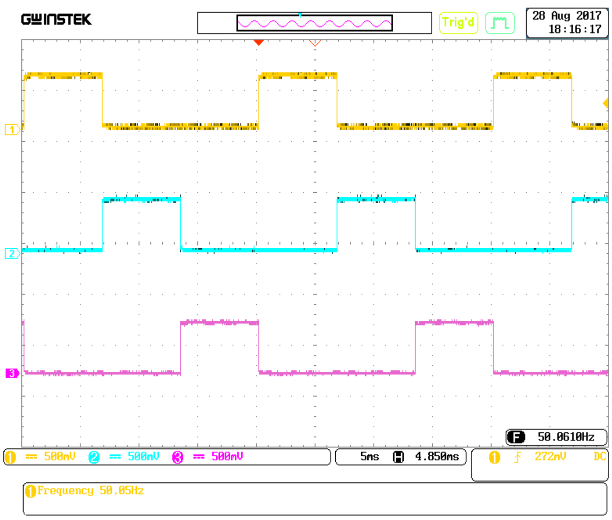

Figure-14. The switching signals of S_1, $S_3$and S_5 for 120^0conduction mode.

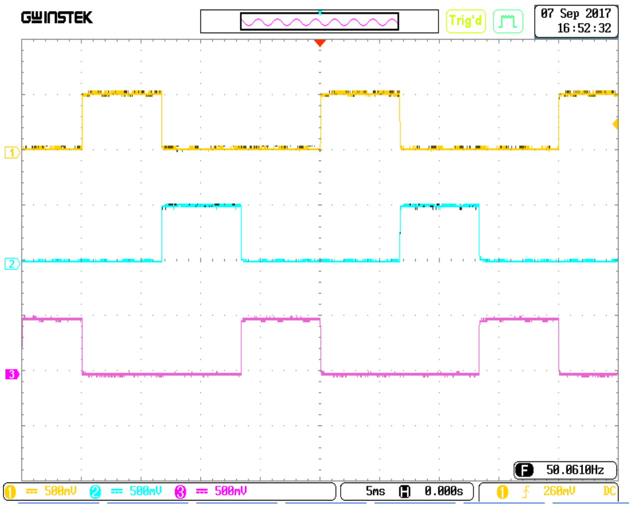

Figure-15. The switching signals of S_2, S_4 and S_6 for 120^0conduction mode.

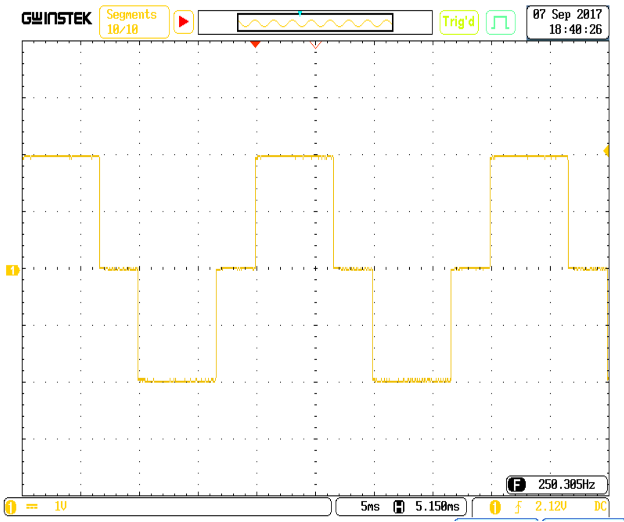

Figure-16. The output voltage waveform (V_{LN}) for 120^0 conduction mode.

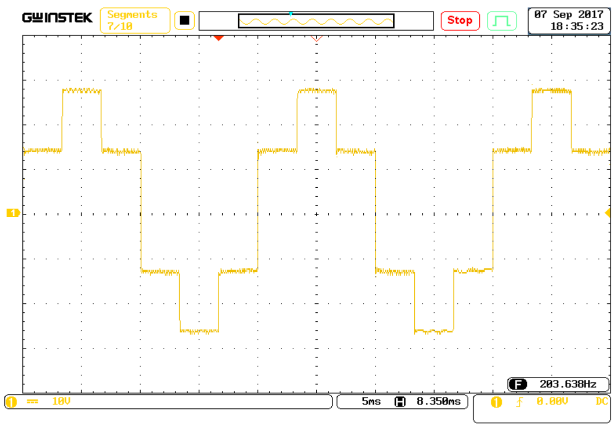

Figure-17. The output voltage waveform (V_{LL}) for 120^0 conduction mode.

Figures 18 to 21 show the experiment results of three-phase inverter in 180^0 conduction mode. The gating

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signal for S_1, S_3 and S_5 is shown in Figure-18 while the gating signal for S_2, S_4 and S_6 is shown in Figure-19. Each power switch is turned-on in every π radian. The phase voltage output (V_{LN}) contains four DC level voltages while the line voltage output (V_{LL}) only has three level DC voltage, as presented in Figures 20 and 21, respectively.

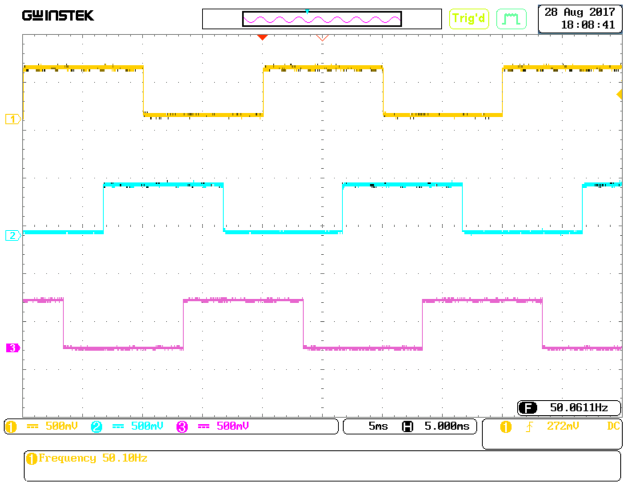

Figure-18. The switching signals of S_1, S_3 and S_5.

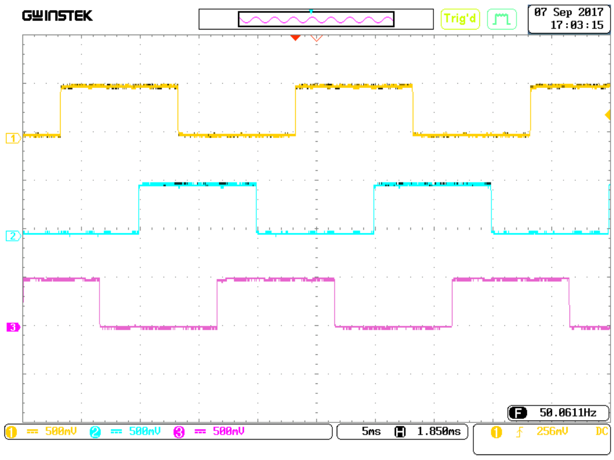

Figure-19. The switching signals of S_2, S_4 and S_6.

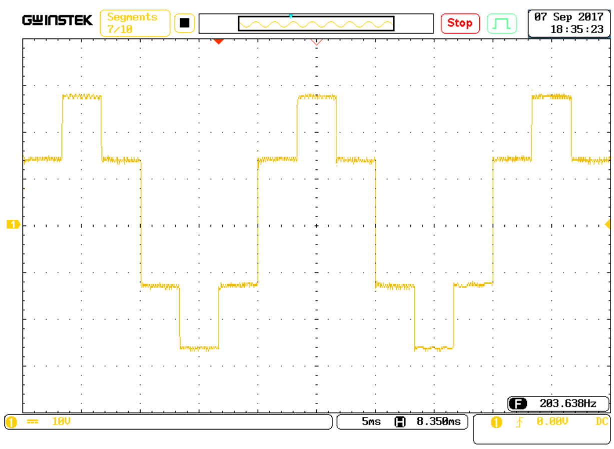

Figure-20. The output voltage waveform (V_{LN}) for 180^0 conduction mode.

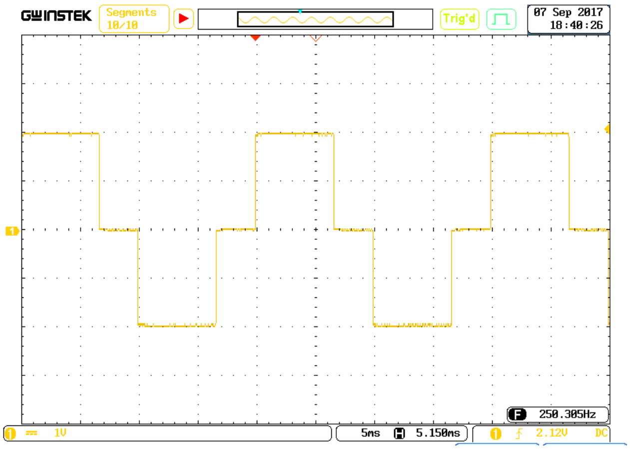

Figure-21. The output voltage waveform (V_{LL}).

CONCLUSIONS

A microcontroller based three-phase inverter scheme for the implementation of a stand-alone PV power generation system has been proposed. Low switching frequency algorithm with 120^0 and 180^0 conduction mode were implanted in the microcontroller target board. This low cost processor has been successfully applied for three-phase inverter. The algorithm of switching angles has been engaged with ATmega8535 and verified by experiment results. The 120^0 conduction mode of three-phase inverter generate three level of voltage output waveform for phase voltage (V_{LN}) and four level output voltage waveform for line voltage (V_{LL}). In contrary, the 180^0 conduction mode of three-phase inverter generate four level voltage output waveform for phase voltage (V_{LN}) and three level voltage output waveform for line voltage (V_{LL}).

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