Effect of Maximum Voltage Angle on Three-Level Single Phase Transformerless Photovoltaic Inverter Performance

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Abstract
This paper presented a new topology of three-level single phase transformerless photovoltaic inverter (TPVI). It consisted of three main circuits; they were a pulse driver circuit, a full bridge inverter circuit and a power factor correction (PFC) circuit that had functions as production of pulse waves, to develop alternating current (AC) waveform and to stabilize voltage of photovoltaic (PV) array, respectively. The TPVI was installed in front of Centre of Excellent for Renewable Energy (CERE), Universiti Malaysia Perlis, in Northern Malaysia. Its main energy source was a PV array that consisted of three unit PV modules, each unit had 81 V, 60 W. In this research, AC three-level waveform single phase TPVI was developed and created by a microcontroller PIC16F627A-I/P with varied maximum voltage angle from 20^0 to 180^0 and observed on 28th February 2014 between 9.00 am to 17.00 pm, and also analyzed effect of maximum voltage angle on the three-level single phase TPVI performance. The result showed that maximum voltage angles of the TPVI effected on root mean square value of AC voltage, current and power. If the maximum voltage angle was increased, therefore value of the AC voltage, current and power would increase. The maximum voltage angle would effect on the current total harmonic distortion (CTHD), the lowest CTHD of 15.448% was obtained when the maximum voltage angle was 134^0

Keywords: *transformerless PV inverter, AC waveform, solar irradiance, temperature*

1. Introduction

The direct current (DC) electrical energy of PV module can be converted to AC electrical energy using inverter. The 1.5 kW inverter using full bridge topology is designed and tested by [1]. It gave an excellent result for the high power PV module application. An alternative approach of inverter is proposed by [2] to replace the conventional method with the use of microcontroller. The use of the microcontroller brings the flexibility to change the real-time control algorithms without further changes in hardware. It is also low cost and has small size of control circuit for the single phase full bridge inverter.

In grid or off grid connected installation, the inverter input power is determined by the solar irradiance on the PV module, that is, both the efficiency and the electricity supply quality depend on the inverter work point (obviously this depends on the solar irradiance incident on the surface of the PV module) [3].

This paper presents a new topology of three-level single phase transformerless PV inverter. It consists of three main circuits; they are a pulse driver circuit, a full bridge inverter circuit and a power factor correction circuit. The advantage of the proposed topology compared to the conventional inverter is low cost, small size, high efficiency, the pulse waves to drive the full bridge inverter circuit is easy to create using the microcontroller PIC16F627A-I/P in which maximum and zero voltage angle of AC waveform can be created. Effect of the maximum voltage angle on three-level single phase transformerless PV inverter performances (rms value of the AC voltage, current, power and also CTHD) is observed and analyzed.

2. Research Method
2.1. Solar Irradiance and PV Array

The transformerless PV inverter is installed in Perlis, Northern state of Malaysia. Its main energy source is a PV array that consists of three unit of 81V, 60W PV modules. The PV array converts solar energy (solar irradiance) to be DC electricity. In this research, the solar irradiance is recorded by a weather station every minute as shown in Figure 1.

Figure 1. Weather Station and PV Array

2.2. Componenets of Proposed Topology

The realized system is a typical stand alone single phase transformerless PV inverter that can feed AC loads. The complete system is shown in Figure 2 that consists of three main circuits; they are a pulse driver circuit, a full bridge inverter circuit and a power factor correction circuit. Detail circuit of the each circuit is explained below.
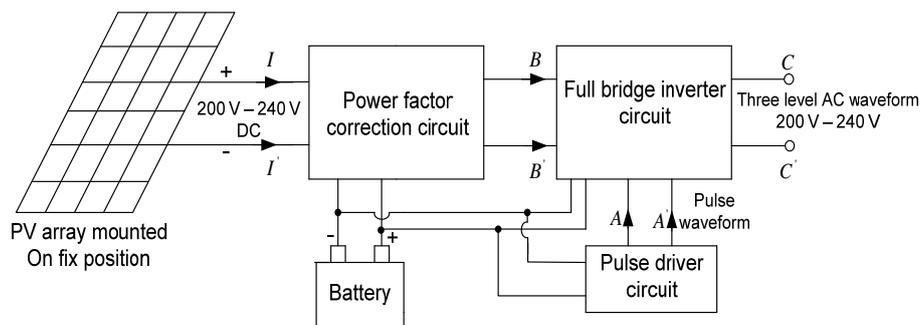

Figure 2. Realized Single Phase TPVI System

The pulse driver circuit is used to produce two pulse waves that needed to drive the full bridge inverter circuit. The pulse waves are developed by a microcontroller PIC16F628A-I/P as shown in Figure 3. A listing program is created to produce the pulse waves using C language in PIC C compiler and formed at pin 11 and 12 of the microcontroller.

The full bridge inverter circuit is used to produce an AC waveform that input signal is the two pulse waves. The circuit is modification result of [4] as shown in Figure 3. The point A and $A^{'}$ are pulse wave input signal terminals that needed to drive the circuit, the point C and $C^{'}$ are AC output waveform that its magnitude depends on DC input at point B and $B^{'}$ around 200 V – 240 V.

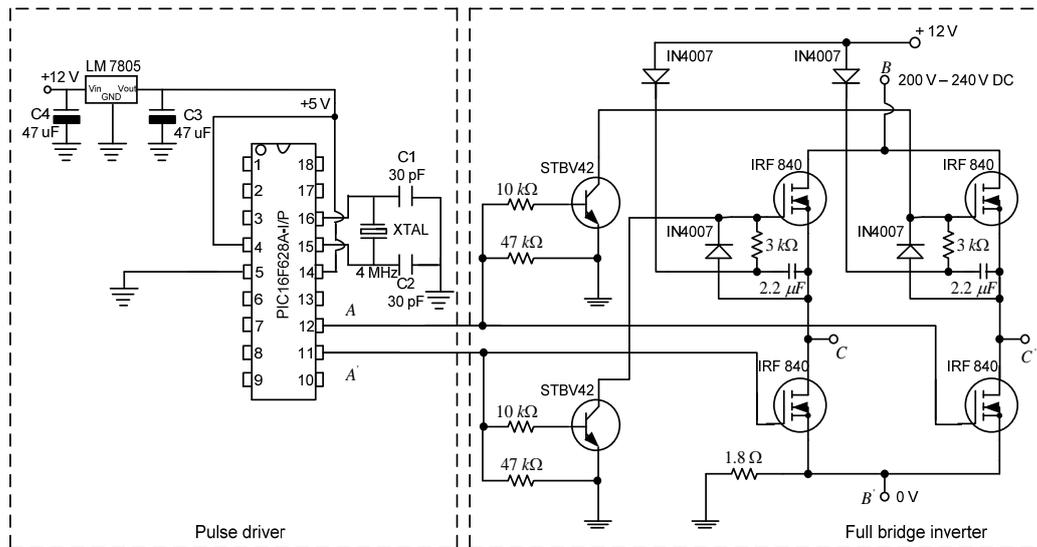*Effect of Maximum Voltage Angle on Three-Level Single Phase Transformerless… (M. Irwanto)*

Figure 3. Pulse Driver and Full Bridge Inverter Circuit

The power factor correction circuit is used to stable DC voltage that produced by the PV voltage. The circuit is modification result of [5] as shown in Figure 4. The point I and $I^{'}$ are input voltage terminal which supplied by the PV array. The output of this circuit at point B and $B^{'}$ is connected to the full bridge inverter circuit.
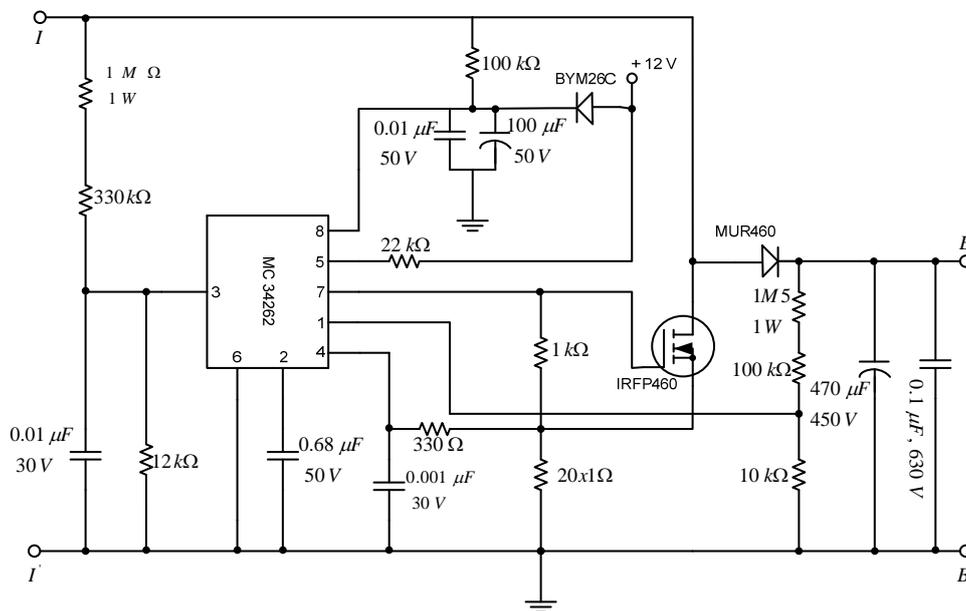

Figure 4. Power Factor Correction Circuit

2.3. Operation Principle of Proposed Topology

The simplest technique to convert DC power into AC power is to generate a square wave. However, the harmonic content of the square wave is relatively high, also the efficiency of this waveform is relatively low [6-8]. The three-level inverter is explained and analyzed by [8], its efficiency is significantly higher and harmonic contents are less than the square wave [9].

Normally, the low frequency (50Hz) inverter uses a transformer that it is big, heavy and expensive. To reducing the manufacturing cost, size, and weightof the system, the transformerless inverter is suitable [10-16]. It improves the system efficiency. Transformerless inverter concept is advantageous because of their high efficiencies which can be reached of up to 97-98% [12].

Figure 5 shows two operation modes of the proposed transformerless PV inverter (TPVI). It has a phase leg including S_1 and S_2 operating at the system period of 20 ms, and another phase leg including S_3 and S_4 commutating at the switching period. Two additional switches S_5 and S_6 may commutate either at the system period or at the switching period to achieve two DC states. According to two operation modes which generate the voltage state of positive or negative polarity at point C or $C^{'}$.
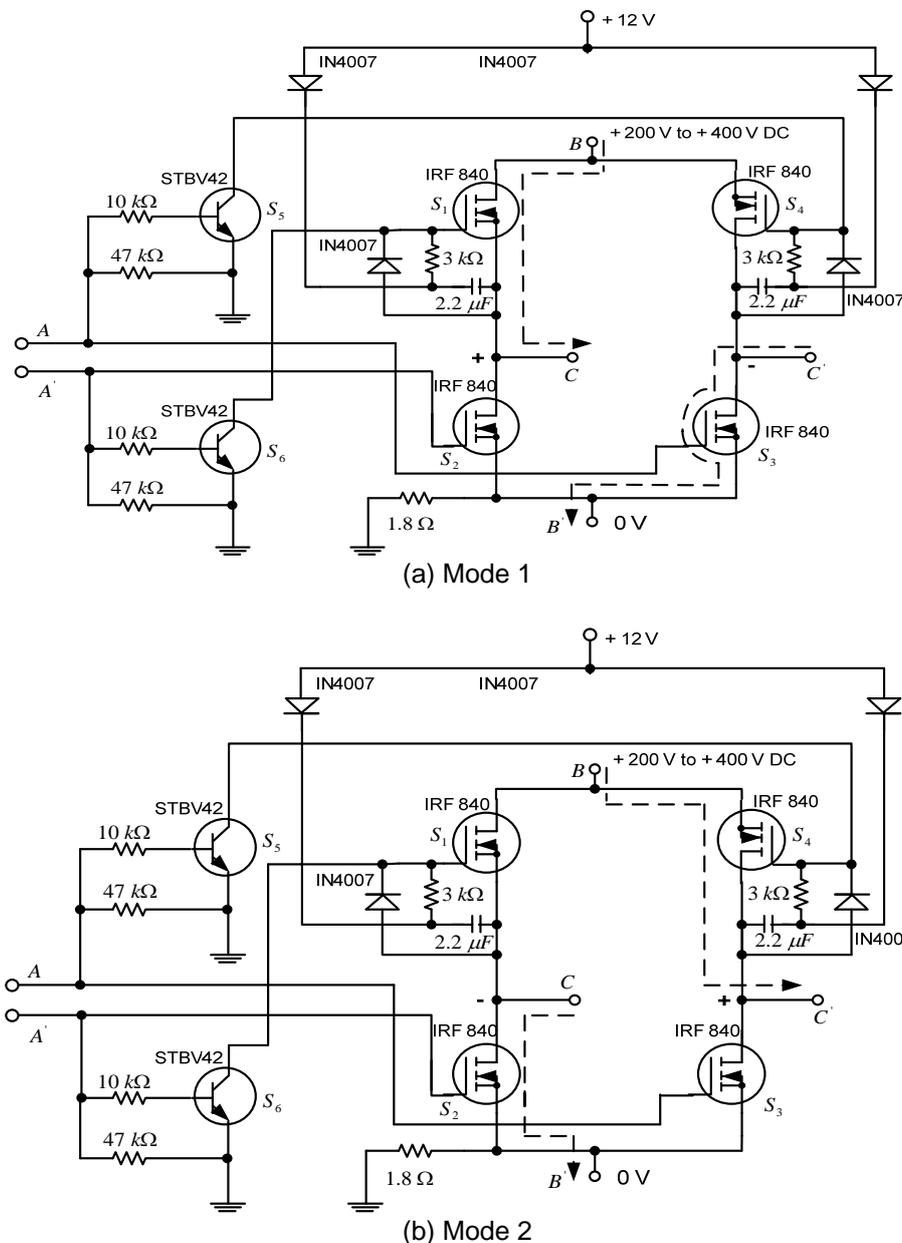

(a) Mode 1

(b) Mode 2

Figure 5. Two operation modes of proposed TPVI

The PV output voltage of 200V to 240V is fed to input of the PFC circuit. The out put of the PFC circuit is fed to the full bridge inverter circuit at point B and $B^{'}$. The full bridge inverter circuit is drived by two pulse waves at point A and $A^{'}$ (as shown in Figure 6) that created by the microcontroller PIC16F627A-I/P as shown in Figure 3. The operation principles of three-level waveform trasformerless inverter below are analyzed.

200V to 240V DC is supplied to the full bridge inverter at point B and $B^{'}$ in Figure 3. Mode 1 in Figure 5, the capacitors of 2.2 μF are charged by 12V through diodes IN4007. Thus the MOSFET, S_1 and S_4 are on. Operation principle of the transformerless PV inverter is explained for the time of 20 ms that divided by four parts.

a) At the first time of α ms, point A has a pulse wave and point $A^{'}$ is zero, S_3 is on, transistor, S_5 gets on thereby grounding the gate of S_4, turning S_4 off. Thus for α ms S_1, S_3 are on and current flows from B to S_1 to C to $C^{'}$ to S_3 and to $B^{'}$. For this cycle, point C has positive polarity and $C^{'}$ has negative polarity, thus the inverter output voltage has positive value around +200 V to +240 V as shown in Figure 6.

b) At the second time of β ms, point A and $A^{'}$ have zero pulse wave, transistor, S_5, S_6 and MOSFET, S_1, S_3 are off. There is no current flow through the load, thus the inverter output voltage at point C and $C^{'}$ is zero as shown in Figure 6.

c) At the third time of α ms, mode 2 in Figure 5, point $A^{'}$ has a pulse wave and point A is zero, S_2 is on, transistor, S_6 gets on thereby grounding the gate of S_1, turning S_1 off. Thus for α ms S_2, S_4 are on and current flows from B to S_4 to $C^{'}$ to C to S_2 and to $B^{'}$. For this cycle, point C has negative polarity and $C^{'}$ has positive polarity, thus the inverter output voltage has negative value -200 V to -240 V as shown in Figure 6.

d) At the fourth time of β ms, point A and $A^{'}$ have zero pulse wave, transistor, S_5, S_6 and MOSFET, S_1, S_3 are off. There is no current flow through the load, thus the inverter output voltage at point C and $C^{'}$ is zero as shown in Figure 6.
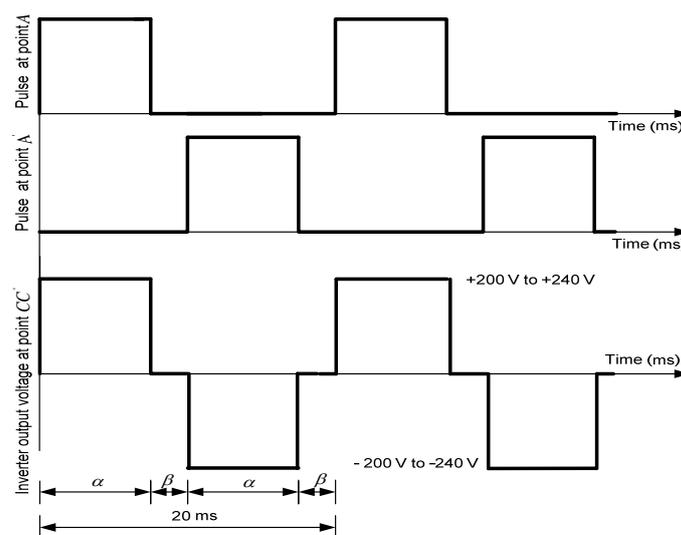

Figure 6. Pulse and Three-level Output Waveform of the TPVI

Figure 6 shows that waveform of the three-level single phase transformerless PV inverter output voltage has a system frequency of 50 Hz or system period of 20 ms. Zero and maximum voltage angle, β and α of the waveform will effect on performances of the transformerless PV inverter (rms voltage, V_{rms}, peak voltage, V_p, efficiency, η_i, and current total harmonic distortion, CTHD). Relationship between α and β in ms is derived as below:

$$2\alpha + 2\beta = 20$$
$$2\beta = 20 - 2\alpha$$

$$\beta = 10 - \alpha \tag{1}$$

2.4. Experimental Setup

Main experimental setup equipments of the single phase TPVI consist of PV array, pulse driver circuit, full bridge inverter circuit, power factor correction circuit, battery, and two load types, the first is inductive load of 20W, 220V, 50Hz AC water pump and the second is 30W resistive lamp load. The measurement equipments consist of Vantage Weather Station Pro2, voltage logger, and PM 300 Analyzer. The experimental setup is shown in Figure 7.

Figure 7. Experimental Setup

As shown in Figure 7, the TPVI input is connected to the PV array and its output is connected to the load of 20W, 220V, 50Hz AC water pump and 30W resistive lamp load. The PV array output voltage is measured by voltage logger which its value depends on solar radiation and temperature. The solar irradiance and temperature are measured by the Vantage Weather Station Pro2. Performances of the load are measured by the PM 300 Analyzer. The measurements are real time system and recorded every minute.

3. Results and Analysis
3.1. Solar Irradiance, Temperature on 28th February 2014

In this research, AC single phase waveforms of the TPVI are developed and created by the microcontroller PIC16F627A-I/P and observed on 28th February 2014 from 9.00 am to 17.00 pm, and also analyzed their performance. The solar irradiance and temperature are shown in Figure 8. The average solar irradiance is 691.2 W/m^3, it indicates that the sky is clear and suitable to generate the PV power generation [17].
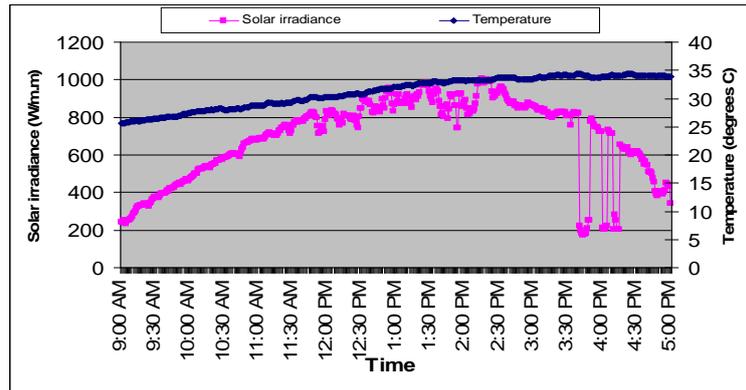
Figure 8. Solar Irradiance and Temperature on 28th February 2014

3.2. Effect of Maximum Voltage Angle Change on AC Voltage and Current Waveform of Single Phase TPVI

The solar irradiance and temperature as shown in Figure 8 will effect on the PV array output voltage. If the solar irradiance increase and assuming the temperature is constant will cause the PV array output voltage increase, otherwise if the temperature increase and assuming the solar irradiance is constant will cause the PV array output voltage decrease [18].

AC single phase waveforms of the TPVI varying maximum voltage angle that created by PIC16F627A-I/P were observed on 28th February 2014 for condition of solar irradiance, temperature, PV array voltage as shown in Figure 9. Every maximum voltage angle was observed through 5 minutes, and value of solar irradiance, temperature were recorded by weather station and PV array voltage by voltage logger.
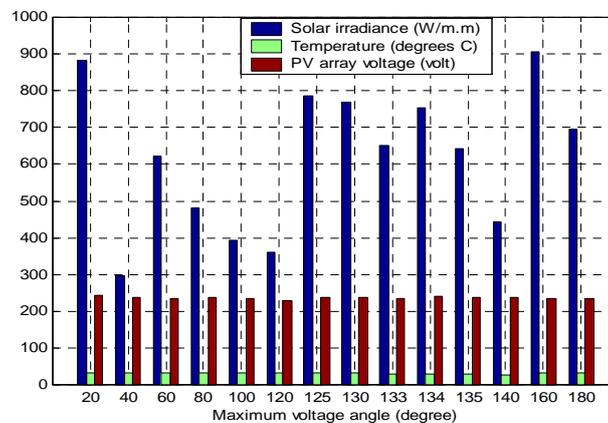
Figure 9. Condition of Solar Irradiance, Temperature and PV Array Voltage Varying Maximum Voltage Angle

Figure 9 show that each maximum voltage angle was observed on solar irradiance was higher than 250W/m², it indicates that it was suitable to generate the PV array generation. The PV array voltage of each condition of solar irradiance, temperature was higher than 230V. The PV array voltage was fed to input of the power factor correction circuit at point I and $I^{'}$ as shown in Figure 4 and its output was fed to the full bridge inverter circuit at point B and $B^{'}$ as shown in Figure 3 and 5, at point C and $C^{'}$ produced an AC waveform. For the each condition of solar irradiance, temperature and PV array voltage as shown in Figure 9 produced an AC voltage and current waveform of the TPVI as shown in Figure 10.
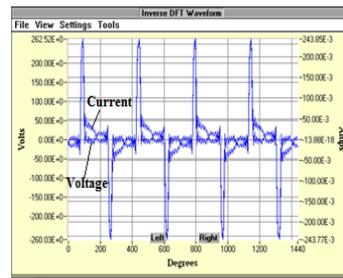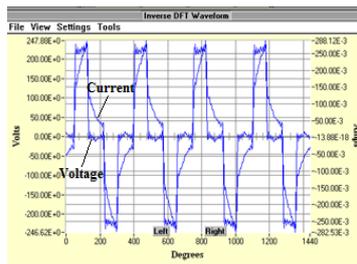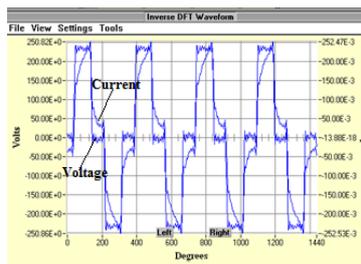
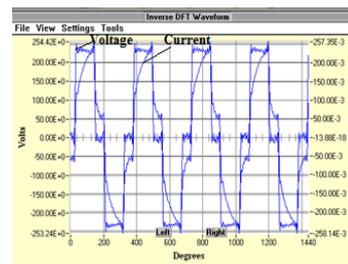(a) Maximum voltage angle at 20^0
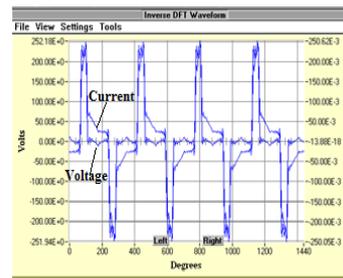
(b) Maximum voltage angle at 40^0
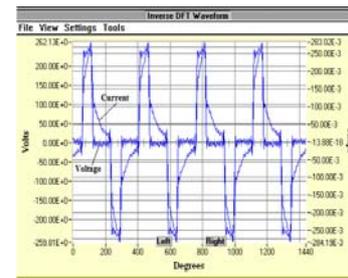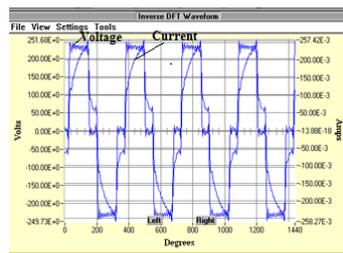

(c) Maximum voltage angle at 60^0
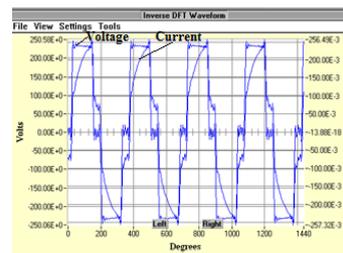

(d) Maximum voltage angle at 80^0

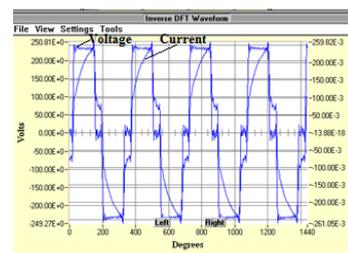(e) Maximum voltage angle at 100^0

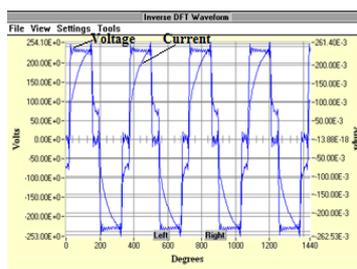(f) Maximum voltage angle at 120^0
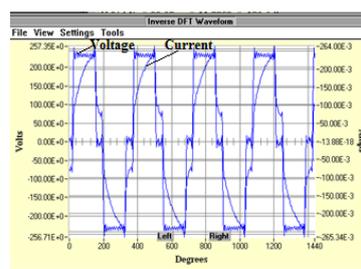

(g) Maximum voltage angle at 125^0

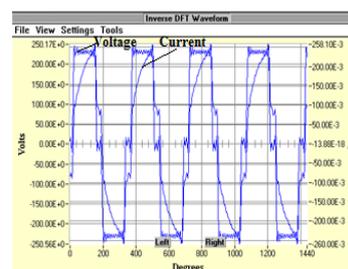(h) Maximum voltage angle at 130^0

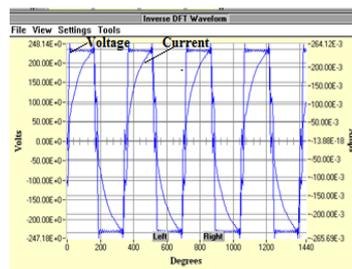(i) Maximum voltage angle at 133^0
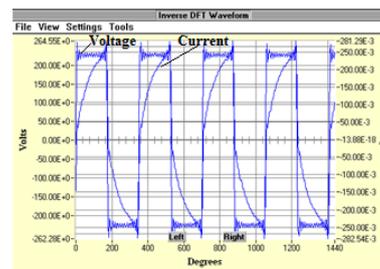

(j) Maximum voltage angle at 134^0

(k) Maximum voltage angle at 135^0

(l) Maximum voltage angle at 140^0

(m) Maximum voltage angle at 160^0

(n) Maximum voltage angle at 180^0

Figure 10. AC Voltage and Current Waveform of the TPVI

Figure 10 shows that change of maximum voltage angle of AC waveform of the TPVI will effect on value of the AC voltage and current waveform. If the maximum voltage angle was increased, therefore value of the AC voltage and current waveform would increase as shown in Figure 11 and 12, respectively. They also will effect on the power, if the maximum voltage angle was increased, therefore the active, reactive and apparent power would increase as shown in Figure 13.

In the experimental set up, the inductive load of 20W, 220V, 50Hz AC water pump and the 30W resistive lamp load were connected to the TPVI, therefore AC current flows through the loads. There was no significant effect on the different angle between AC voltage and current or power factor when the maximum voltage angle was changed. As shown in Figure 10, the AC waveforms leaded the AC current waveforms by 20.16^0 or the power factor was 0.94.
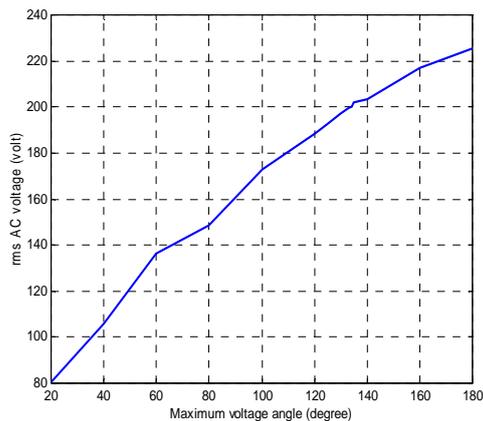

Figure 11. Effect of Maximum Voltage Angle on the AC Voltage
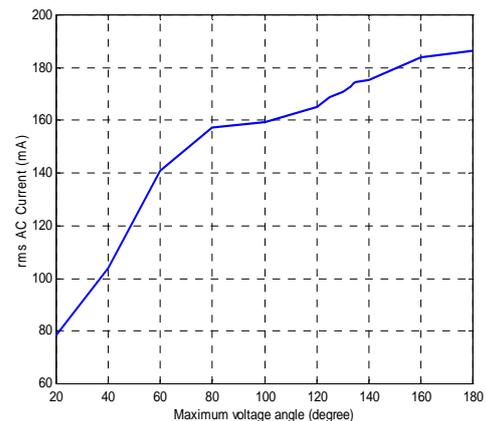

Figure 12. Effect of Maximum Voltage Angle on the AC Current

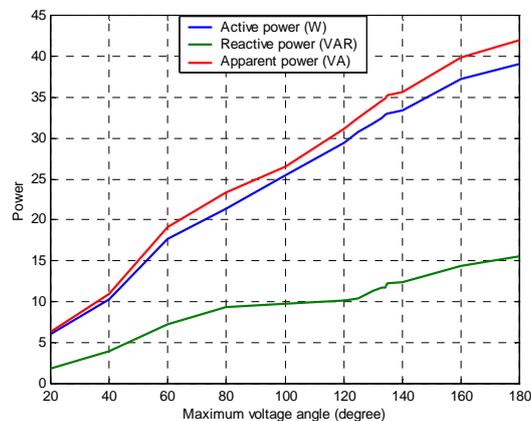Figure 13. Effect of Maximum Voltage Angle on the AC Power

3.3 Effect of Maximum Voltage Angle Change on Current Total Harmonic Distortion (CTHD)

The inductive load of 20W, 220V, 50Hz AC water pump and the 30 W resistive lamp load which were connected to point C and $C^{'}$ of the full bridge inverter circuit produced current harmonic spectrum and CTHD in which their value depended on type of the AC waveform.

When the maximum voltage angle was 20^0, AC voltage and current waveform of the TPVI was not perfect as shown in Figure10 (a), therefore it produced a highest CTHD ofv108.94 % as shown in Figure 14.

A three-level AC waveform started to be developed when the maximum voltage angle was 40^0 as shown in Figure 10 (b). It produced a lower CTHD of 74.33 % as shown in Figure 14. It was lower CTHD compared to the CTHD that produced by the maximum voltage angle of 20^0.

When the maximum voltage angle was increased from 60^0 to 133^0, the AC voltage and current waveforms were more perform as shown in Figure 10 (c) to (i), they produced lower CTHD.

A CTHD was obtained when the maximum voltage angle was 134^0. Its AC three-level waveform is shown in Figurer 10 (j), its CTHD of 15.448 % is shown in Figure 14. The maximum voltage angle was a optimal angle to obtain a lowest CTHD.

If the maximum voltage angle was increased again from135^0 to 180^0 as shown in Figure 10 (k) to (n), therefore the current harmonic spectrum and CTHD would increase back as shown in Figure 14.
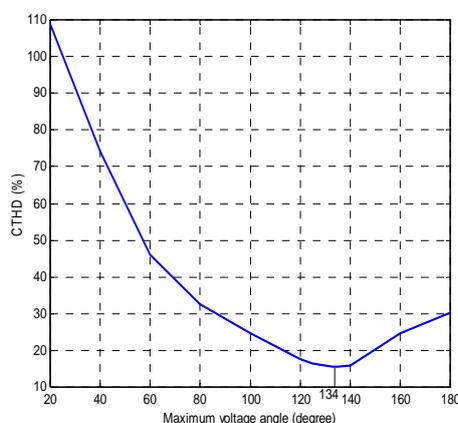

Figure 14. Effect of Maximum Voltage Angle on Current Total Harmonic Distortion (CTHD)

4. Conclusion

According to result shown, the proposed topology can be applied to the three-level single phase TPVI, from the results can be summarized as below:
a) Performance of the three-level single phase TPVI depends on the solar irradiance and temperature. The solar irradiance of 250 W/m^2 and above, it was enough to develop AC waveform of the single phase TPVI.
b) Maximum voltage angles of the TPVI effect on value of AC voltage, current and power. If the maximum voltage angle was increased, therefore the value of AC voltage, current and power would increase.
c) The maximum voltage angle would effect on the CTHD, the lowest CTHD of 15.448% was obtained when the maximum voltage angle was 134^0.

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