Single Phase Five Level Multistring Multi-level Inverter For Distributed Energy Resource (DER)

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Abstract—**Nowadays most inventors and scientist are addicted to research on renewable energy especially solar photovoltaic (PV) energy to connect it into the grid system. This system consists of main parts such as inverter, transformer, filters and others. This paper presents the new simplified topology of five-level multistring multi-level inverter especially for distributed energy resources (DER). In this paper, the aim is to construct the simplest topology of inverter to replace the conventional inverter in order to reduce the cost and size as well increase the performance. MOSFET was used as the main switching devices because of the higher switching frequency and can operate at higher power. Besides, those MOSFETs are easier to control since it is a voltage control component. This simplified inverter can give five level output waveform to obtain more smooth output AC and consequently reduce the filter size. The LC filter also included in this design to regulate the AC output waveform. The powerful software such PSIM used in this design to simulate the circuit. Besides, the total harmonic distortion, THD also been considered in order to achieve the best performance of this simplified inverter.**

Keywords-Induction Photovoltaic (PV), Multi-level Inverter, Total Harmonic Distortion (THD), PSIM, AC, Transformer, MOSFET.

I. INTRODUCTION

Nowadays, renewable energy resources became most important electrical energy supply. As a prove, based on statistic of Germany, from 1990 to 2001 solar PV capacity has increased more than 50% per year while solar PV electricity production increases nearly 60% per year [1]. The solar PV system is one of the renewable energy resources that convert solar energy directly into electrical energy. The basic device that used in the conversion Solar PV system is known as solar cell which first produced in 1954. Solar cell principally converts flux of radiation into a current source [2]. Since PV panel consist of multiple solar cell only generates power during sunlight, the energy storage is required to power up the loads during the non sunlight time. Usually, the battery was used as energy storage and the output source for battery are in DC [3, 4]. Therefore, inverter required to convert the DC source into the AC source in order to connect it into the grid system.

The inverter is one of the important parts in solar PV system. Inverters also known as DC-AC converter where it receives DC power input while deliver AC powers as output [5-7]. The AC output voltage in practice is not in sinusoidal form as well the output is in stages and contains certain harmonics but it's still acceptable for low and medium power applications [8]. In addition, multiple stage of inverter is known as multi-level inverter where it can be configure start from three levels, four levels, five levels and more[9].

Multi-level inverter is the main objectives of this paper. There are numerous types of conventional multi-level inverter topology such as diode-clamped inverter (DCM), flying capacitor inverter (FCI), cascaded H-bridge inverter (CHBI), etc [5, 6].

However, there are several weaknesses for conventional multi-level inverters. The obvious weakness is the production cost of this inverter is higher. The inverter built up from a combination of high power switches such as MOSFET's, and IGBT's that required high gate to source, or gate to emitter voltage to drive the switches. Since the microcontroller gives the low voltage output signal to drive those switches, thus driver circuit is required to drive the switches which as well increase the cost of production [10]. Harmonic distortion is known as high frequency components of current or voltage in electrical system where it can degrade the equipment or by overheating it [5]. It can be measured by calculating the total harmonic distortion (THD) percentage. The higher THD percentage also became one of the weaknesses of these conventional inverters.

As a solution of those weaknesses, this paper presents the new topology of multistring five-level multi-level inverter that design especially for distributed energy resources (DER) [7]. DER is electric generation units within the power ranges between 3kW to 50MW located within the electric distribution system at or near the end user. They connected in parallel to the electric utility or stand-alone units which also known as generators, back-up generators, or on-site power systems. There are several types of DER technologies such as Energy Storage/UPS, Photovoltaic Systems, Wind Systems, Combustion Turbines and others [11]. Figure 1 shows the type of DER technologies.

The simplified inverter improves by reducing the number of switches for five-level multi-level inverter to 6 switches. Furthermore, this topology used MOSFET as switches since it can operate at higher powers and higher switching frequency. Thus this invention reduces the number of components as well reduce the cost. This design was simulated using PSIM and the prototype has been fabricated to examine the effectiveness and reliability of this simplified inverter. As for prototype, PIC microcontroller used to control the MOSFETs gate voltage by injecting signals since the cost of PIC is much lower. The PIC generates Pulse Width Modulation (PWM) signals based on the modulation technique used to control those MOSFETs. However, the MOSFETs switching frequency for prototype device is lower due to limitation of microcontroller used.

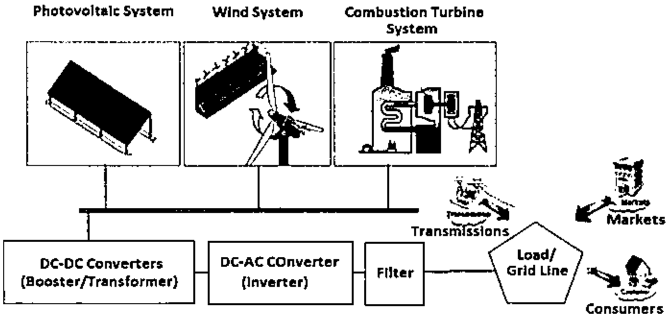

Figure 1: Distribution Energy Resources

II. SYSTEM DESCRIPTION

Figure 2 show the block diagram circuit for this simplified inverter. The full circuit that studied in this paper consists of the simplified inverter circuit, LC filter circuit, MOSFET driver circuit, and controller circuit. Since the main objectives of this paper are to study the topology of the inverter, the step-up circuit to increase the DC power is not included to apply it on the real application. Thus, the prototype only tested at small powers. However, this design still can be improved by providing a booster circuit instead of transformer to step-up the DC power in order to reduce the harmonic distortions as well reduce the size of this inverter.

To test the reliability of this simplified circuit, this project was simulated by using PSIM software and the THD also has been analyzed in order to achieve the lowest percentage. Besides, other software was also used to support this project such as Xilinx ISE design tool which support the simulation circuit design and Mplab 8.3 and Proteus ISIS used to support the prototype design. The purpose of the Xilinx ISE design tool was to generate the decoder circuit based on the binary logic input using Verilog programming. The Mplab 8.3 was used to compile and burned the signal into the PIC microcontroller while Proteus ISIS was used to test the programming signal that generates by Mplab application.

This simplified inverter circuit feed by two DC supply voltages which make it suitable to use in DER system. In practical design, the MOSFETs were controlled by controller circuit that consists of the PIC microcontroller. The signals programming is written based on the output waveform from the simulation. Since the output voltage from microcontroller circuit is between 3V to 5V, MOSFET driver circuits are required to control the MOSFETs gate voltage. Then, the output voltage from the simplified inverter circuit was filtered by an LC filter in order to obtain smooth sinusoidal waveform.

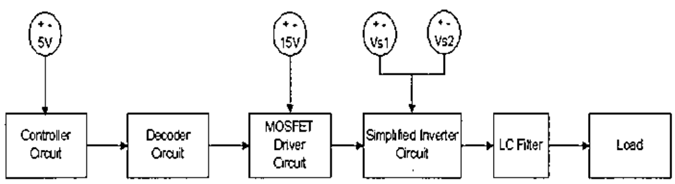

Figure 2: Block Diagrams of Simplified Inverter Circuit

A. Simplified Inverter Circuit

Inverter circuit is a main circuit and function to convert DC power to AC power. This simplified circuit generates five-level AC output stages only by using six switches instead of eight switches in CHBI [5, 6]. There are three PWM signal used to control those switches which are A, B and C.

Figure 3 show the simplified circuit of the inverter. This inverter feeds by two DC supplies with six switches. Those switches were controlled by PWM signal. In simulation, Phase Disposition PWM (PDPWM) modulation technique introduced in this paper to control four switches includes S_{a1}, S_{a3}, S_{b1} and S_{b3} while S_{a2} and S_{b2} are controlled by 50% duty cycle signal. PDPWM generates by comparison of sinusoidal waveform and triangular carrier waveform [12]. Figure 4 illustrated the arrangement circuit for a PDPWM method with switching frequency, f_s = 500Hz and modulation index, m_a = 0.95 while Figure 5 showed the output logic waveform from comparison between triangular and sinusoidal waveforms.

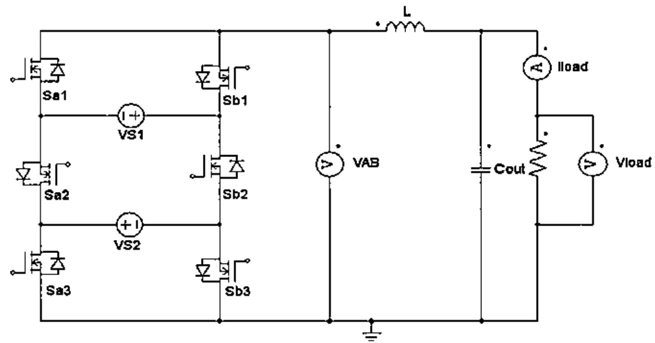

Figure 3: Simplified Inverter Circuit

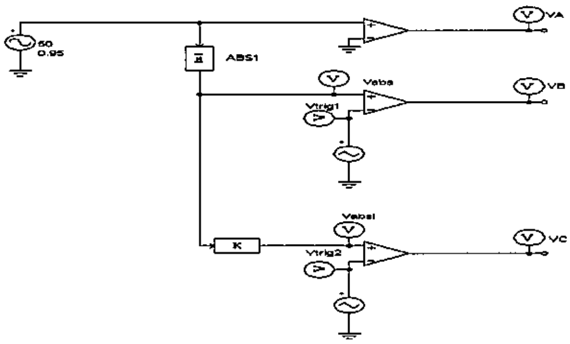

Figure 4: Modulation Circuit

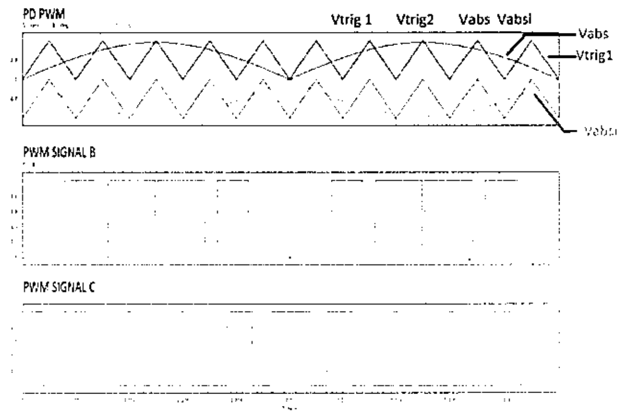

Figure 5: PDPWM Signal with Output Signal

Based on Figure 5, the PWM signal B and C obtain from PDPWM technique as discuss in [12] are decoded by decoder circuit into six signals to control all MOSFETs as showed in Figure 12.

The principle operation of this simplified inverter showed in the truth table from Table 1. The explanation of operation described as below:

1) For positive voltage source 1, V_{S1} level, it occurs when the switches S_{b1}, S_{a2}, S_{a3} are switched on. In the other hand, the positive voltage source 2, V_{S2} level occurs when switches S_{a1}, S_{a2} and S_{b3} are switched on. Figure 6 and Figure 7 showed the circuit conduction at those levels.

2) To obtain positive maximum voltage, $2V_S$, switch S_{b1}, S_{a2} and S_{b3} are switched on. Figure 8 showed the circuit conduction at this level.

3) At negative voltage source 1, $-V_{S1}$ switches S_{a1}, S_{b2}, S_{b3} will turn on while at negative voltage source 2, $-V_{S2}$ switches S_{b1}, S_{b2}, S_{a3} are switched on. Figure 9 and Figure 10 showed the conduction at those levels.

4) As for maximum negative voltage source, $-2V_S$ the switches S_{a1}, S_{b2} and S_{a3} are switched on. Figure 11 showed the conduction circuit at this level

In practical design, MOSFET driver circuit is required. Thus, to determine the suitable driver, this simplified circuit analyzed properly. Based on Figure 3, the connection of switches Sa1 and Sb1 is in half bridge connection which V_{S1} is the source voltage. Same as combination of switches Sa3 and Sb3 where V_{S2} is the source voltage. Therefore, two half bridge MOSFET driver circuits are required. Based on Figure 12, the output waveform from decoder circuit, switches Sa2 and Sb2 only applied 50Hz switching frequency with higher voltage stress compared to others switches as shown in switching point in Table 1. Besides, from Figure 12, the switching signal for combinations of switches 1 (S_{a1}, S_{b1}), 2(S_{a2}, S_{b2}) and 3 (S_{a3}, S_{b3}) are inverted between the side a and side b. Therefore, to reduce the prototype circuit components, decoder circuit can be neglected since four output signals, Sa1, Sa2, Sb2 and Sa3 as in Figure 12 can be directly programmed into the microcontroller while another's two output signal is inverted from programmed signal. In addition, the output voltage, V_{out} can be calculated according (1).

$$V_{out} = (V_{s1} + V_{s2}).m_a \tag{1}$$

Table 1: Truth Table for MOSFETs Switching

A	B	C	S_{a2}	S_{b2}	S_{a1}	S_{b1}	S_{a3}	S_{b3}	V
0	0	0	0	1	0	1	0	1	0 V_S
0	0	1	0	1	0	1	1	0	$-V_{S2}$
0	1	0	0	1	1	0	0	1	$-V_{S1}$
0	1	1	0	1	1	0	1	0	$-2V_S$
1	0	0	1	0	0	1	0	1	$+2V_S$
1	0	1	1	0	0	1	1	0	$+V_{S1}$
1	1	0	1	0	1	0	0	1	$+V_{S2}$
1	1	1	1	0	1	0	1	0	0 V_S

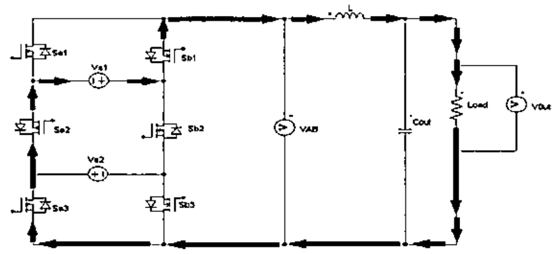

Figure 6: Positive V_{S1}

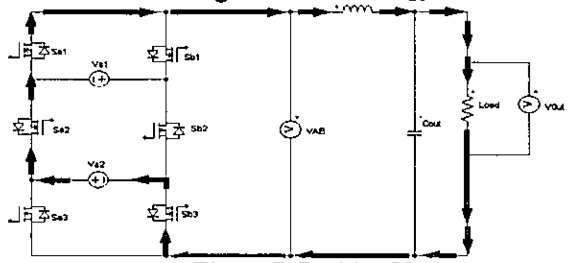

Figure 7: Positive V_{S2}

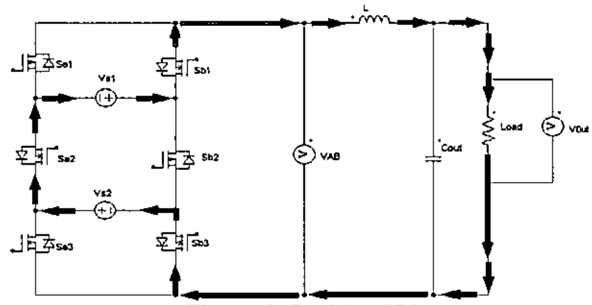

Figure 8: Positive $2V_S$

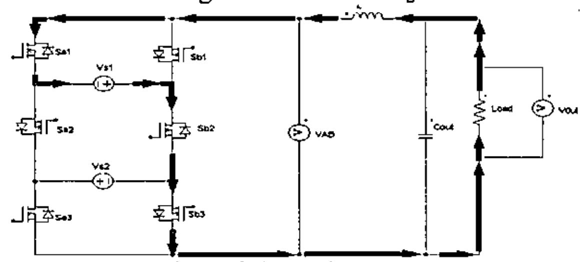

Figure 9: Negative V_{S1}

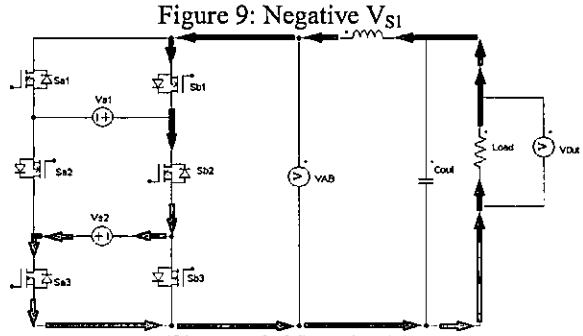

Figure 10: Negative V_{S2}

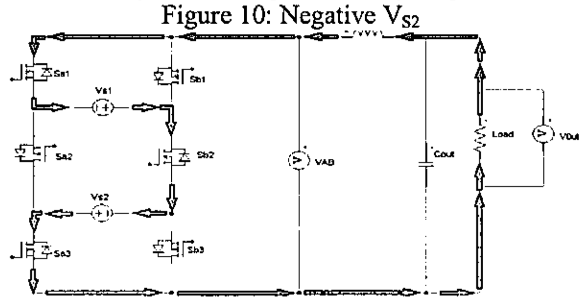

Figure 11: Negative 2VS

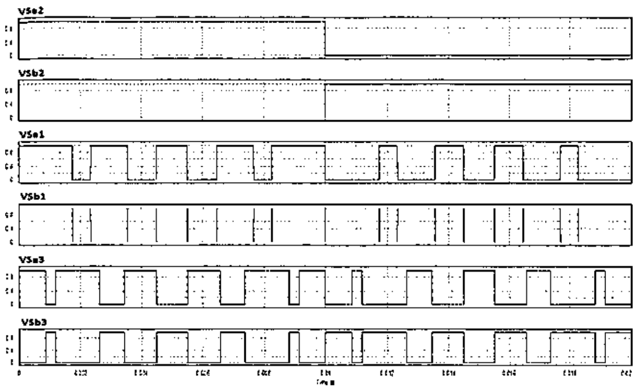

Figure 12: Decoder Circuit Output Waveform at f_s = 500Hz

B. MOSFET Driver Circuit

This circuit only applied in practical design. The output voltage from controller circuit to drives the MOSFETs is insufficient since the voltage range required to drive the MOSFETs gate voltage is between 15V to 30V while the output voltage from controller circuit is about 3V to 5V. Therefore, this driver circuit is required to drive the MOSFET. Besides, the supply used to operate this circuit is different from controller circuit. Thus, optocoupler device is required to separate those connections.

C. Decoder Circuit

There are six MOSFETs used in this circuit and six switching signal also required to drive those MOSFETs. Thus, in order to reduce the generating signals, decoder circuit decoded three input signals, signals A, B and C to six output signals, S_{a1}, S_{a2}, S_{b1}, S_{b2}, S_{a3} and S_{b3} that controls the MOSFETs. The logic circuit invented based on truth tables in Table 1. The truth table obtains based on the conduction circuit at various levels as shown in Figure 6 to Figure 11. To obtain the sinusoidal output signals, PDPWM method used in this project as described in [12]. PDPWM operates by comparing one sinusoidal waveform with two triangular waveforms such showed in Figure 4 and Figure 5. However, this circuit only applies in simulation since in the prototype circuit; the output switching signal can be programmed directly.

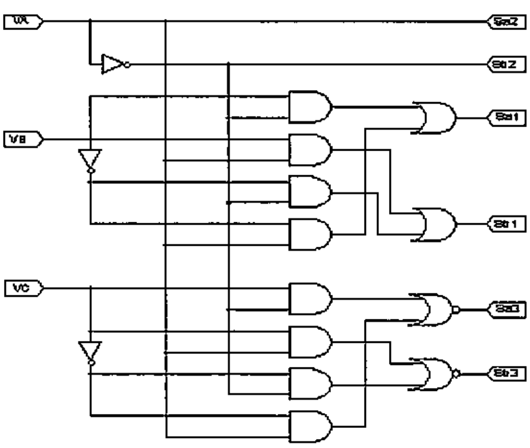

Figure 13: Decoder Circuit

D. Controller Circuit

This circuit also only applies in practical design in order to generate signals to control those switches. In simulation, the signals are generated by modulation circuit in Figure 4 and decoded by decoder circuit by using PDPWM technique.

E. Filter Circuit

LC filter applied as filter circuit. It's also known as resonant circuit which function to minimize the low frequency ripple as well reduce the harmonic distortion [13]. The parameters consider in designing this filter are inductor, capacitor and switching frequency. The calculation can be done according (2).

$$\sqrt{LC} = \frac{1}{2\pi f_s} \quad (2)$$

F. Comparison With CHBI

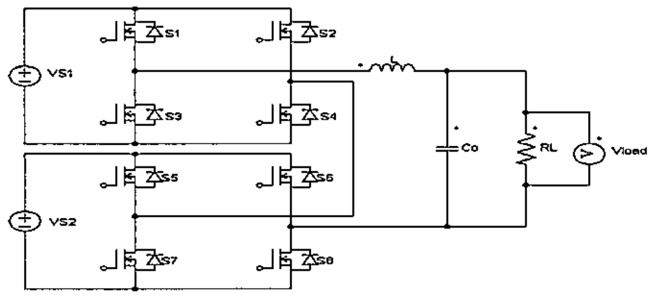

Figure 14: Cascaded H-Bridge Multilevel Inverter (CHBI) [12]

Table 2: Comparison between CHBI and Proposed Inverters

Types of Inverter	CHBI	Simplified Inverter
Switches	8	6
Voltage Stress	S1-S4 = V_S S5-S8 = V_S	Sa1,Sb1,Sa3,Sb3 = V_S Sa2,Sb2 = 2 V_S
Switching Frequency	S1-S8 = high frequency	Sa1,Sb1,Sa3,Sb3 = High Frequency Sa2,Sb2 = line frequency

The CHBI as showing in Figure 14 have been compared with the simplified inverter. Based on Table 2, Simplified inverter showed more advantages where it significantly reduces in number of switches. Besides, Sa1, Sb1, Sa3 and Sb3 are operated at single voltage supply while only Sa2 and Sb2 operated at double voltage supply compare to CHBI all switches operated at single voltage supply. As for switching frequency for CHBI is at high frequency for all switches while switches Sa2 and Sb2 in simplified inverter can operate at line frequency, 50Hz. Therefore, the proposed inverter is more reliable compared to CHBI.

III. METHODOLOGY

The new single phase multistring simplified inverter has been proposed after some research and literature review done based on conference paper and the journal. Then, this simplified inverter circuit executed to check whether the conceptual theory can be applied or not. Therefore, the simplified inverter circuit implemented into PSIM application software together with the modulation and decoder circuit in order to apply the PDPWM technique to this inverter.

The flowchart for the process of implementing this simplified inverter showed in Figure 15. The description of the flowchart is described as below:

- Start research about the project by doing the literature review in multi-level inverter based on types and modulation technique.
- Design and simulate the proposed circuit. A Xilinx ISE design tool used to design decoder circuit part using Verilog programming based on the truth table in Table 1. Then, decoder circuit simplified until showed in Figure 13.
- Determination of modulation technique used by entering three input signals into decoder circuit and obtain six output signals for controlling the MOSFETs. Modulation technique chooses is a PDPWM technique [12].
- Overall circuit then simulated using PSIM application software in order to examine the lowest output THD and smooth AC waveform.
- Subsequent to success simulation, proceed to develop the prototype of this inverter where it consists of two parts, hardware and software. Hardware needs are, driver circuit, simplified inverter circuit and microcontroller circuit. As for software, the PIC programming has been developed to produce six output signals from decoder circuit to drive the MOSFETs. Then, the programming developed interface with the PIC circuit.
- Analysis of the output waveform and THD percentage evaluated by comparing the result of simulation and the tested prototype circuit. The expected result of prototype circuit should be lower than simulation due to losses in the components.

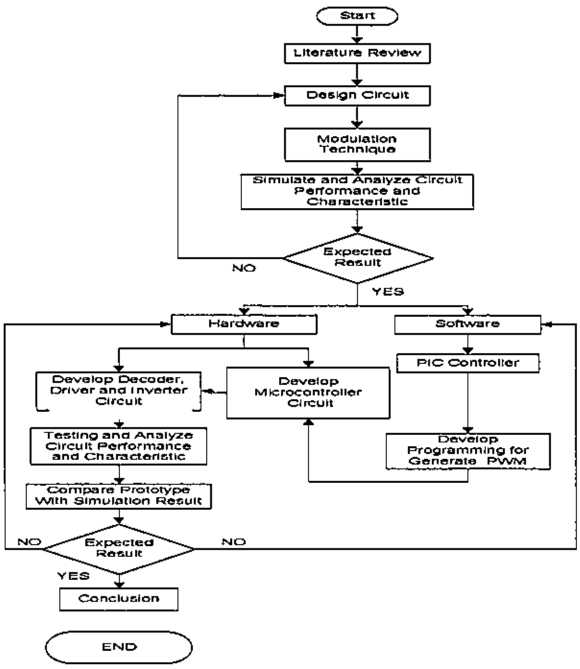

Figure 15: Flow Chart of Project Development

IV. RESULT AND DISCUSSION

A. Simulation Using PSIM

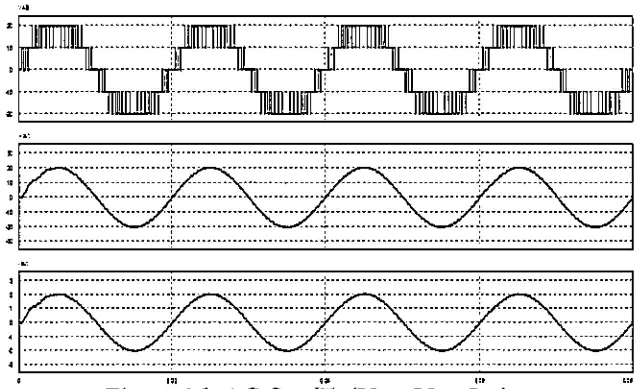

Figure 16: AC Output (V_{AB}, V_{out}, I_{out})

This simplified inverter has been simulated by using PSIM application software and THD has been analyzed. THD percentage can be calculated according (3).

$$THD = \sqrt{\frac{H_1{}^2+H_2{}^2+\cdots+H_n{}^2}{H_1{}^2}} \tag{3}$$

Figure 16 illustrated the AC output powers from the simplified inverter which is V_{AB}, V_{out} and I_{out} at 1 kHz switching frequency. As for the parameter of this simulation, the inductor, L used is 1mH while the capacitor values used depend on switching frequency. The voltage supply for this experiment, V_s = 10V each and load = 10 Ω. The peak output voltage, V_{out} for simulation is 20V while for peak output current, I_{out} is 2A.

B. Hardware Implementation

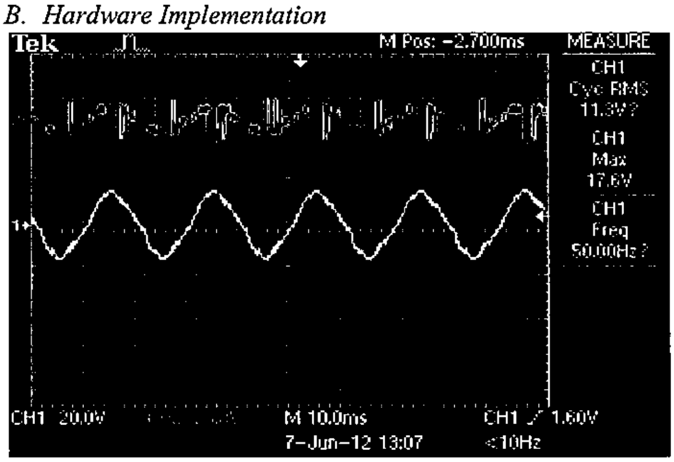

Figure 18: Output Signal for Prototype Circuit

Hardware has been implemented to verify the reliability of this simplified inverter. The output waveform for V_{AB}, V_{out} and I_{out} showed in Figure 18. The THD percentage for experiment showed in Figure 19 and Figure 20. The parameter for this experiment is same with the simulation parameter. The peak output voltage, V_{out} obtain from experiment is 17.6V while for peak output current, I_{out} is 1.44A as shown in Figure 18.

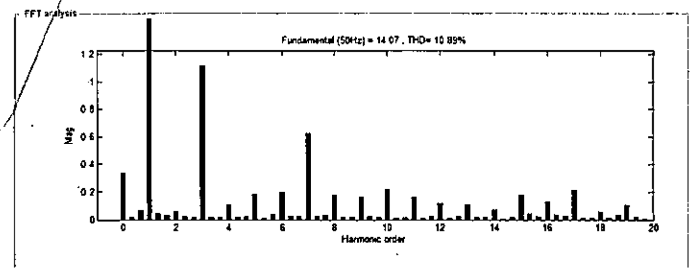

Figure 19: THD Percentages for Output Voltages

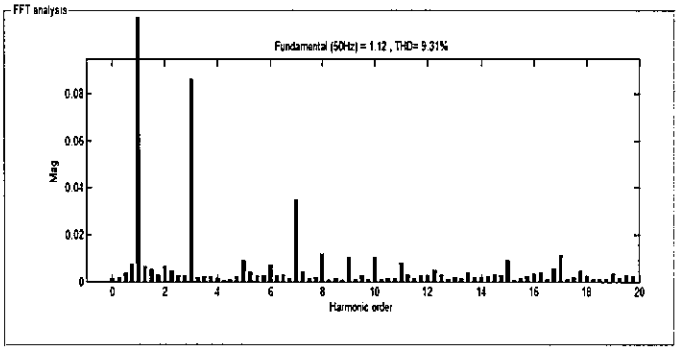

Figure 20: THD Percentages for Output Currents

C. Comparison between Simulation and Experiment Result

Table 3: Comparison between Simulation and Experiment Result

	Simulation		Experimental
f_s	1kHz	10kHz	1kHz
C_{out}	100uF	10uF	100uF
m_a	1.0	1.0	1.0
V_{out}	20V	20V	17.6V
I_{out}	2A	2A	1.44A
THDP, V_{out}	1.75%	0.17%	10.89%
THDP, I_{out}	1.51%	0.17%	9.31%

Comparison result between simulation and experiment has been made and the result record in Table 3. Based on the simulation result, switching frequency 10 kHz give the lowest THD percentages and the smallest filter size. Even for switching frequency 1 kHz, the THD percentage is still acceptable but required large filter size. Based on experimental result, THD percentage for current is 9.31% while THD percentage for voltage is 10.89%.

Compared to simulation result, the THD percentage for both experimental voltage and current is quite higher due to low switching frequency and voltage drop from MOSFETs and other components. Besides, PIC also has limitation that it executes the coding in sequent. Thus, the delay PWM signal from PIC is not precise since it required to generate fours signals simultaneously also affected the experimental result.

However, this topology circuit still can be applied to real application but required improvement in controller circuit such Xilinx or DSP controllers. Besides, higher rating power for components should be consider since the component of this experiment has a lower rating due to lower power tested.

V. CONCLUSION

This paper proposes the simplified inverter for DERs application where this topology successfully reduces the switches for five level output. The results obtained also proved the effectiveness and the reliability of this topology through reducing the size of capacitor for filter since small total harmonic distortion percentage achieve for higher switching frequency. In addition, the improvement can be made to apply it in the real application by using a powerful controller such Xilinx. Xilinx can operate at higher speed so that higher switching frequency can be applied.

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