Performance of Nine-Level Transformerless Photovoltaic Powered Inverter (TPVPI) Using Technique of Equal Maximum Phase Delay Time

M. Irwanto1,2, N. Gomesh3, B. Ismail2, H. Alam1, M. Masri1, B. S. Kusuma4

1Department of Electrical Engineering, Institut Teknologi Medan (ITM, Medan, Indonesia
2Fellow of Centre of Excellence for Renewable Energy, School of Electrical System Engineering, Universiti Malaysia Perlis (UniMAP), Perlis, Malaysia
3Engineering Department, School of Engineering, Computing & Built Environment, KDU Penang University College, Pulau Pinang, Malaysia
4Industrial Engineering Department, Universitas Medan Area (UMA), Medan, Indonesia

Abstract. A simple inverter is constructed by some switching components that connected in half bridge or full bridge circuit. The switching component can be a metal oxide semiconductor field effect transistor (MOSFET), transistor or insulated gate bipolar transistor (IGBT) which is driven by simple technique of pulse wave modulation (PWM). This technique generates a square alternating current (AC) waveform but it is still AC pulse wave with rich harmonic production and it is not good for the long life of electric devices. A multilevel inverter is better than the previous inverter. Some techniques have been developed to generate multilevel inverter for main objective to generated AC waveform toward sinusoidal waveform and reduce the harmonic. Also, an inverter is constructed by a transformer which is big in size and produce losses and it can increase the harmonic. This paper presents a nine-level transformerless photovoltaic powered inverter (TPVPI) system using technique of equal maximum phase delay time. It is constructed by two main elements. The first is photovoltaic (PV) module as a main direct current (DC) voltage source and the second is four full bridge circuits in cascaded connection. The proposed technique is that each two MOSFETs for cross position in the same full bridge have a same pattern of pulse wave for the period of 0.02 s. It has a phase delay time of 0.00111 s for generating the nine-level AC waveform.

1. Introduction
Nowadays, the renewable energy plays an important position in energy resources after occurring the energy crisis some years ago. Photovoltaic (PV) is one part of renewable energy. It has more application compared the other type of renewable energy. It is due to that the main energy conversion is solar energy [1].

The conversion of DC output voltage of PV module to be AC voltage can be done by using an inverter. Normally, a transformer is applied in the inverter that it is expensive, heavy and bigger in size. A transformerless inverter is suitable to solve this problem as stated by [2] – [7]. A three-level transformerless inverter has been constructed by [8]-[12]. The main components are PV module as DC voltage source and switching components in full bridge circuit.

A mention of multilevel inverter is started by three-level inverter. The five-level inverter has AC
waveform and harmonic which it is better than three-level inverter, and the seven-level inverter is also better than the five-level inverter, and the nine-level inverter is the best compared to the three, five and seven-level inverter in term of the generated waveform and harmonic.

This paper presents a nine-level transformerless photovoltaic powered inverter (TPVPI) system. Some PV modules in series connection are as DC main voltage source for the input voltage of full bridge circuit. There are four full bridge circuits in cascaded connection to generate the nine-level waveform. A technique of equal phase delay time is applied in the TPVPI system to generate the nine-level voltage waveform.

2. Methodology

The proposed technique of equal maximum phase delay time on nine-level TPVPI system is presented in this section. This section explains how nine-level output voltage of TPVPI system can be generated based on the equal maximum phase delay time. The meaning of equal maximum phase delay time, circuit of nine-level inverter and pulse waves generated by each switching components are also explained in this section. Lastly, the nine-level TPVPI system is implemented using SIMULINK MATLAB.

2.1 Proposed nine-level inverter using technique of equal phase delay time

The maximum phase delay time means a phase delay time needed by a multilevel waveform when it reaches a maximum value, and the equal maximum phase delay time means that the phase delay time reached by every waveform level equals the maximum phase delay time, \( t_{mpd} \) as shown in Figure 1 and Equation (1).

\[
\begin{align*}
    t_{pd1} &= t_{pd2} = \ldots = t_{pd(m-1)/2} = t_{pd(m+1)/2} = t_{mpd} \\
    t_{mpd} &= \text{maximum phase delay time for positive waveform}
\end{align*}
\]
\[ t_{pdm} = \text{phase delay time for m-level} \]
\[ t_{pd(3(m-1)/2)+2} = \text{maximum phase delay time for negative waveform} \]
\[ t_{pd(2(m-1)+2)} = \text{the last phase delay time} \]

There are \(2(m-1)\) for the number of switching components and \(2(m-1) + 2\) for the number of phase delay time on the m-level waveform. Figure 2 shows a proposed circuit of nine-level inverter and pulse waves created by switching components. The switching components are connected in Full bridge circuit and it has four full bridge circuits. Each full bridge circuit has four switching components and each two switching components in cross position has same pulse wave as shown in Figure 2.

50 Hz nine-level output voltage of inverter is created in the design. It has a period of 0.02 s. For the nine-level, the number of phase delay time is \(2(9-1) + 2 = 18\) and the phase delay time is \(0.02 \text{ s} / 18 = 0.00111 \text{ s}\). The time of 0.00111 s is also maximum phase delay time and equals the phase delay time reached by every waveform level.

![Figure 2. A circuit of nine-level inverter and pulse waves created by switching components](image)

### 2.2 Nine-level TPVPI using SIMULINK MATLAB

The modelling of nine-level TPVPI using SIMULINK MATLAB consists of modelling of PV module, modelling of nine-level inverter and lastly is complete system modelling of nine-level TPVPI system. The overall modelling of nine-level TPVPI system following some steps below:

a. Modelling of PV module
20.64 V, 20 W Shinyoku PV module is modelled using SIMULINK MATLAB. Its data sheet for the electrical parameters is shown in Table 1. The block set of PV module of SIMULINK MATLAB is applied and its block parameter is filled following Table 1 as shown in Figure 1 (a). The complete PV modelling consists of PV module block set, controlled voltage source and measurement block set as shown in Figure 1 (b). The input of PV module block set is solar irradiance and temperature that each value affects the performance of PV module. The output of PV module is output voltage as shown by positive terminal of PV module (+PV) and negative terminal of PV module (-PV) in Figure 1 (b). The output voltage terminals of PV module are connected to the block set of controlled voltage source and measurement with its complete block set as shown in Figure 1 (c). It is needed to capture the constant output voltage of PV module for a required solar irradiance and temperature. The block set of gain indicates series connection of some PV modules.

A test of error percentage is applied to state the modelling of PV module is valid or not following an error percentage value of ±10% [13]. The electrical parameter validation of PV module performance based on the current-voltage and power-voltage curve on the standard test condition (STC) by clicking the plot button in Figure 3 (a).

### Table 1. Electrical parameter of 20.64 V, 20 W Shinyoku PV module

| Parameters                        | Value  |
|-----------------------------------|--------|
| Maximum power (W)                 | 20     |
| Short circuit current (A)         | 1.3    |
| Open circuit voltage (V)          | 20.64  |
| Voltage at the maximum power (V)  | 17.2   |
| Current at the maximum power (A)  | 1.16   |

(a) Block parameter of PV module
b. Modelling of nine-level inverter

The modelling of nine-level inverter is based on Figure 2. Each full bridge circuit is constructed by four MOSFETs and four full bridge circuits are connected in cascaded connection. Each gate, G terminal of MOSFET is driven with phase delay time and pulse width as shown in Table 2 for the period of 0.02 s. It is generated using block set of pulse generator.

| MOSFET  | Phase delay time (s) | Pulse width (s) |
|---------|---------------------|-----------------|
| S<sub>1</sub>, S<sub>3</sub> | 0.00111 | 0.00777 |
| S<sub>2</sub>, S<sub>4</sub> | 0.0111 | 0.00777 |
| S<sub>5</sub>, S<sub>7</sub> | 0.00222 | 0.00555 |
| S<sub>6</sub>, S<sub>8</sub> | 0.01221 | 0.00555 |
| S<sub>9</sub>, S<sub>11</sub> | 0.00333 | 0.00333 |
| S<sub>10</sub>, S<sub>12</sub> | 0.01322 | 0.00333 |
| S<sub>13</sub>, S<sub>15</sub> | 0.00444 | 0.00111 |
| S<sub>14</sub>, S<sub>16</sub> | 0.01443 | 0.00111 |

c. Modelling of complete TPVPI system

The modelling of complete TPVPI system as shown in Figure 4 is combination of PV module modelling as shown in Figure 1 and nine-level inverter modelling. The output terminal of inverter is connected a resistive load of 15 W. The performance of nine-level TPVPI system is observed and analysed.
3. Result and Discussion

The nine-level TPVPI system is operated directly by PV modules connected to each full bridge circuit. The performance results of PV module modelling are validated to the data sheet at STC and also the performance results of nine-level TPVPI system in term of load voltage, current and total harmonic distortion (THD) are discussed in this section.

3.1 Validation of PV module performance

The modelling of PV module as shown in Figure 3 (b) is given solar irradiance of 1000 W/m² and temperature of 25°C. The power-voltage and current-voltage curve are shown in Figure 5 and Figure 6, respectively. The comparisons of the data sheet and simulation results as validation are shown in Table 3. They show that the error percentage of maximum power, open circuit voltage and short circuit current are 0.25%, 0% and 0%, respectively. They are in the range of ±10 % and close or equal 0%, thus the simulation results are acceptable as stated by [13].
Figure 5. Current-voltage curve of 20.64 V, 20 W Shinyoku PV module at STC

Figure 6. Power-voltage curve of 20.64 V, 20 W Shinyoku PV module at STC
Table 3. Comparison of data sheet and simulation results for 20.64 V, 20 W Shinyoku PV module at STC

| Parameters                  | Data sheet | Simulation | Error percentage (%) |
|-----------------------------|------------|------------|----------------------|
| Maximum power (W)           | 20         | 19.95      | 0.25                 |
| Open circuit voltage (A)    | 20.64      | 20.64      | 0                    |
| Short circuit current (A)   | 1.3        | 1.3        | 0                    |

3.2 Performance of nine-level TPVPI System

The nine-level TPVPI system is designed with voltage magnitude around 310 V. It needs four PV modules in series connection for each full bridge circuit. It can be done by filling the block set parameter of gain as shown in Figure 3(c) by 4.

Each full bridge circuit is supplied by voltage of 79.52 V generated by four PV modules connected in series as shown in Figure 4. These voltages create the voltage levels in nine-level voltage waveform as shown in Figure 7 for each phase delay time of 0.000111 s. It has maximum voltage level of 310.10 V as duplicated results of each full bridge circuit voltage supply (it is around 4 x 79.52 = 318.08 V). It can be seen that there is voltage drop around 318.08 – 310.10 = 7.98 V. The voltage drop occurs on the switching components (MOSFETs). If the nine-level inverter circuit created by sixteen MOSFETs, thus each MOSFET has voltage drop of 7.98/16 = 0.50 V.

An active power of 15 W is connected to the output terminal of nine-level TPVPI system. It flows current with a current waveform as shown in Figure 8 and it has maximum current level of 4.65x10^{-5} A. The pattern of current waveform is same with the pattern of voltage waveform, exactly nine-level waveform. The current waveform is in phase of the voltage waveform, it means that the system has unity power factor. The nine-level TPVPI system also has THD of 26.27 % as shown in Figure 9.

![Figure 7. Load voltage of nine-level TPVPI system](image1)

![Figure 8. Load current of nine-level TPVPI system](image2)
4. Conclusion
The simulation of nine-level TPVPI system has been conducted. It includes the modelling and simulation of PV module, also the modelling and simulation of nine-level inverter. Some statements can be concluded following the simulation results:

20.64 V, 20 W Shinyoku PV module is modelled and simulated, its electrical parameter results are compared to the datasheet. It shows that the simulation results is acceptable and it can be implemented as DC voltage source of the full bridge circuits.

Nine-level TPVPI system is created using a technique of equal maximum phase delay time. It has each phase delay time of 0.00111 s. The nine-level voltage waveform generated has maximum voltage of 310.10 V for each PV module voltage of 79.52 V.

Acknowledgements
This work was supported in part by the Indonesian Ministry of Education, Research and Technological under World Class Research Grant for period 2019-2020.

References
[1] Saleh K, Irwanto M, Haziah A. H, Ismail B, Gomesh N, Alam H, Masri M and Irwan Y. M 2017 Estimation of Solar Irradiation in Medan Using Hargreaves Method Based on Minimum and Maximum Temperature for Potential Assessment of Photovoltaic Power Generation Advanced Science Letters 23(2017) 003
[2] Kavidha B and Rajambal K 2006 Transformerless Cascaded Inverter Topology for Photovoltaic Aapplications Proceeding of Indian International Conference on Power Electronics 328-331.
[3] Gonzales R, Lopez J, Sanchis P, Gubia E, Ursua A and Marroyo L 2006 High-efficiency transformerless single-phase photovoltaic inverter, IEEE Explore
[4] Lopes O, Teodorescu R. and Gandoy J.D 2006 Multilevel transformerless topologies for single-phase grid-connected converter IEEE Explore.
[5] Yang B, Li W, Deng Y, He X, Lambert S and Pickert V 2006 A novel single-phase transformerless photovoltaic inverter connected to grid IEEE Explore.
[6] Kusakawa M, Nagayoshi H, Kamisako K and Kurokawa K 2011 Further Improvement of a Transformerless, Voltage-Boosting Inverter for AC Modules Solar Energy Materials & Solar Cells 67(2007) 008.
[7] Patrao I, Figueres E, Espin F.G and Garcera G 2011 Transformerless Topologies for Grid-Connected Single-Phase Photovoltaic Inverters Renewable and Sustainable Energy Reviews 15(2011)008.

[8] Irwanto, M 2014 Comparative Study on AC Square and Three-Level Wave Form of Photovoltaic and Wind Power Hybrid Single Phase Inverter International Journal of Engineering Sciences & Research Technology, 3(10)007.

[9] Irwanto, M, Mansur, T. M. N. T, Irwan, M, Gomesh, N 2012 Optimum Maximum Voltage Angle and Current Total Harmonic Distortion of Uninterruptible Power Supply on Three Level Single Phase Photovoltaic - Wind Power Hybrid Inverter Power Engineering and Optimization Conference (PEOCO).

[10] Irwanto, M, Irwan, Y.M, Gomesh, N, Ahmad, N. S, Hadi, S. P 2012 Maximum Voltage Angle Optimization of Uninterruptible Power Supply on Three-Level Transformerless Photovoltaic Inverter International Conference on Innovation, Management and Technology Research (ICIMTR2012), Melaka, Malaysia.

[11] Daut, I, Gomesh, N, Irwanto, M, Irwan, Y.M, Gomesh, N, & Ahmad, N.S 2012 Optimization of Current Total Harmonic Distortion on Three-Level Transformerless Photovoltaic Inverter Journal of Energy Procedia 14(2012)005.

[12] Daut, I, Irwanto, M, Suhelmi, Gomesh, N, Irwan, Y.M, & Fitra, M 2013 High Power Transformerless Photovoltaic Inverter Journal of Energy Procedia 13(2013)007.

[13] Daut I, Irwanto M, Irwan Y.M, Gomesh N and Ahmad N.S 2011 Combination of Hargreaves Method and Linear Regression as a New Method to Estimate Solar Radiation in Perlis, Northern Malaysia Solar Energy 85(2011)009.