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Residential Use of a Grid-Tied Photovoltaic Inverter

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Abstract: This research introduces a grid tie inverter (GTI) for household solar (PV) systems, focusing on the switch mode DC-AC inverter. The proposed GTI utilizes a combination of SPWM (sinusoidal pulse width modulation) and square wave switching strategies. We discuss the hybrid switching approach and simulate the inverter's performance under a grid tie scenario using SIMULINK. Additionally, we outline the plan for electricity supply to the grid.

Keywords: *Grid-tie, sine-wave, photovoltaic, inverter, Wavelength Modulation, Square Wave*

1. **Overview:** The global population growth and rapid economic expansion have led to an increased demand for energy resources, particularly electricity. The International Energy Outlook 2009 projected a significant rise in global energy generation. Traditional methods of energy production, such as burning fossil fuels, are unable to meet this growing demand and have adverse environmental effects, contributing to global warming. As a result, there is a shift towards renewable energy sources to fulfill energy needs. Solar energy, harnessed from the sun, is one such renewable energy source. Photovoltaic (PV) technology, which converts solar energy into electrical power, has evolved significantly since its discovery in 1839 by Alexandre-Edmond Becquerel. PV systems, ranging from small stand-alone units to large grid-connected units, demonstrate this advancement.

2. **The Design Concept:** A traditional inverter comprises two sections: the power circuit and the control circuit. The power circuit typically utilizes IGBT or MOSFET switches, with the basic configuration consisting of four switches, as illustrated in Figure 2. These switches are controlled by signals generated by the control circuit, typically employing analogue op-amp circuits or digital microcontrollers. Pulse width modulation (PWM) is commonly used as the control signal in inverter designs. However, in some designs where output voltage waveform quality is crucial, sinusoidal pulse width modulation (SPWM) is employed to enhance output voltage quality and reduce harmonic content.

   The switching process divides the four switches into two groups: G1 and G2, and G3 and G4. Positive or negative output voltage is generated based on the switching of these groups. The design of a grid tie inverter (GTI) differs slightly from that of a stand-alone inverter or an inverter with an integrated variable speed controller. To connect a GTI to the grid and feed power into it, the output voltage must meet specific standards and guidelines, as outlined by various researchers (M. H. Rashid, 1995; Undeland, T., Robbins, W., and Mohan, N. 1995; V. Meksarik, S. Masri, S. Taib, and C. M. Hadzer, 2007; Soeren Baekhoej Kjaer, John K. Pedersen, Frede Blaabjerg, 2005; Vivek Agarwal and Sachin Jain, 2007).

Voltage, phase, and magnitude must match the grid's specifications. Additionally, the inverter's output voltage frequency needs to precisely match the grid frequency (50Hz in Malaysia). To ensure compliance with these regulations, the grid voltage is sampled and utilized as a reference for the switching signal in the GTI. The load of the GTI differs from that of standalone or variable speed controller inverters. The burden on the electricity grid is substantially higher for the GTI, meaning that the PV power must be forced into the grid by the GTI. Equations 1 and 2 depict the actual and reactive power flow of the GTI into the grid (Hadzer et al., 2003).

$$\text{Real Power, } Q = \frac{V_{\text{inv}} V_{\text{grid}} \sin \sigma}{Z_t} \quad \ldots (1)$$

$$\text{Reactive Power, } Q = \frac{V_{\text{inv}} - V_{\text{grid}} \cos \sigma}{Z_t} \quad \ldots (2)$$

Where:

V_{inv} = Inverter Output Voltage

V_{grid} = Power grid voltage

Z_t = Impedance of the linking line

σ = Angle difference between V_{inv} and V_{grid}

It is evident from Equation 1 that a phase angle of 90 degrees is required to deliver the maximum amount of actual power to the grid. However, this angle should be less than 90 degrees for GTI stability. On the other hand, sin$f_0$sin might have a positive or negative value in Equation 1. Actual power will flow from the GTI to the grid if the output voltage of the inverter is positive and leads the grid voltage; if the value is negative, actual power will flow in the reverse direction.

Designed and Proposed Circuit: The suggested power circuit for the inverter is depicted in Figure 2. It comprises two IGBT gates connected in parallel. The proposed architecture for the control circuit includes digital and analog circuitry. Both the digital circuit, consisting of a microcontroller serving as the control circuit's brain, and the analog circuit generate the signal required to switch the power circuit. These signals are generated and controlled by the digital circuit sequentially.

Proposed Switching Technique: Conventional inverter designs typically use a single type of switching technique. Instead of employing a single switching signal type, the proposed system combines square wave and SPWM. This type of combination switching lowers the switching frequency, significantly reducing the switching loss across the inverter's switches. Figure 4 displays the block diagram of the proposed switching circuit.

To streamline the synchronization process, the proposed design samples the sine wave from the power grid using a voltage transformer to reduce the 230V grid voltage to 5V. This eliminates the need to generate the sine wave from an analog oscillator, microcontroller, or digital-to-analog converter (DAC). One of the crucial requirements for the GTI is that the frequency of the output voltage from the device must match the frequency of the grid voltage when the sine wave sampled from the grid is used to create the SPWM signal. Figure 4 illustrates how a precision rectifier rectifies the sampled sine wave taken from the grid. As shown in Figure 5, the precision rectifier rectifies the sine wave from the grid to the waveform.

In addition to processing the sampled sine wave, a high-frequency triangle wave is needed to generate an SPWM signal. The analog oscillator in this suggested design will also produce a high-frequency triangle wave, with a frequency of 10 kHz, as seen in Figure 6. Afterward, a comparator will process these two signals to create SPWM for the switching signal. As seen in Figure 3, these two signals will result in a unipolar SPWM. The unipolar SPWM signal alternates between +5V and 0V.

The proposed GTI will incorporate a square wave signal for switching in addition to the SPWM signal typically used in many inverter circuits to switch the IGBT. As depicted in Figure 7, this square wave signal will be in phase and at the line frequency (50 Hz for Malaysia). A NOT gate will be employed to produce a different set of signals that are 180 degrees out of phase with the original square wave.

With four MOSFET switches, the inverter requires four sets of switching signals to control the gates after receiving a square wave and SPWM signal. The two sets of square wave signals undergo an AND operation with the SPWM signal to create four sets of signals, which are then used to switch the MOSFET switches, as illustrated in Figure 8. These four switching signal sets can be split into two groupings: SIGNAL (A) and SIGNAL (B) from Figure 8 comprise the first group, while SIGNAL (C) and SIGNAL (D) make up the second group. The first group will flip gates G1 and G2 to produce a positive output voltage for the inverter during the first half of the cycle, while the second group will switch gates G3 and G4 to provide a negative voltage at the inverter's output during the second half of the cycle, as illustrated in Figure 9. This results in the inverter's output voltage prior to the filtering process.

In addition to the analog circuitry generating the square wave and SPWM signals, a digital circuit will be utilized to handle the signal. It is necessary to regulate the signal produced by the analog circuit to ensure proper operation, which is achieved by using a microcontroller. The microcontroller ensures that the triangle wave is in the correct order and that the square wave signal generated by analog means is in phase with the sampled sine wave, as shown in Figure 10.

Power Transmission: As mentioned in Section 2, to deliver power from the GTI to the power grid, the GTI's voltage angle must lead the grid's voltage angle. A phase shifter circuit is incorporated into the system to enable this. Once the sine wave is captured from the grid, it is sent via a phase shifter to create the leading condition.

The ideal leading angle, as indicated in Equation 1, should be 90 degrees to deliver the maximum power to the grid. However, in reality, it won't be precisely 90 degrees due to stability issues. Figure 10 illustrates the real power output as a function of the angle.

Additionally, Zt plays a crucial role in transmitting power to the electrical grid along with the line impedance. To mitigate the impact of harmonics, an LC low-pass filter will be used at the inverter's output in most designs. Equation 1 demonstrates how this LC filter increases Zt and reduces maximum power transmission.

Design Operation: The suggested inverter's operation consists of two components: synchronization and power transmission.

During the synchronization phase, the inverter generates the output in phase with the grid. This is achieved by sampling the sine wave and setting the phase shift to zero. The unshifted sine wave is then rectified to create the SPWM signal, which is compared to a high-frequency triangular wave. After an AND operation with the square wave, four sets of signals are generated, as illustrated in Figure 8. These sets of signals switch the gates of the MOSFET switches accordingly.

Using this type of switching, gates G3 and G4 are forced to the OFF state when gate G2 is ON, and gate G1 is switched using the SPWM signal, resulting in a positive output voltage for the inverter. To generate the negative portion of the output voltage, gates G1 and G2 must be OFF, gate G4 must be ON, and gate G3 is switched by the SPWM signal.

The inverter's output voltage is regulated in phase with the grid when this type of switching and zero phase shifts are used. When the zero crossing of both voltages occurs, indicating that the grid and inverter voltages are in phase, the contactor between the grid and inverter is activated, tying them together.

After the two voltages are connected, the suggested inverter must feed electricity into the grid. In this section, the inverter output voltage is shifted to lead the grid voltage by an angle of using the phase shifter in the proposed inverter's control circuit. With this angle difference, the inverter sends real and reactive power, as indicated by Equations 1 and 2.

Additionally, when the grid loses power, the circuit breaker between the grid and the inverter will trip, isolating the inverter from the grid to prevent unnecessary accidents during a blackout. This islanding operation is achieved by activating the relay shunt, which trips the circuit breaker and uses a current transformer (CT) to monitor the grid. The relay will activate and trip the circuit breaker when the grid loses electricity.

Voltage and Harmonic Output

Amplitude modulation (MA) is a crucial parameter in the switching strategy that significantly influences the performance of the inverter. MA, defined as the ratio of the sine waveform (reference signal, Vr) to the triangular waveform (carrier signal, Vc), is mathematically expressed in Equation 3.

$M=VcVr$

This MA plays a significant role in determining the inverter's output voltage. Theoretically, the AC output voltage of the inverter should increase proportionally with an increase in the MA value. To forecast the output voltage with varying MA values, the suggested switching was simulated using MATLAB Simulink. Figure 12 illustrates the graph of MA against the RMS output voltage for an input DC voltage of 24V.

Figure 12 indicates that as the MA increases, the output RMS voltage also rises. However, this increase has two components: one when MA < 1 and another when MA > 1. When MA is less than 1, the RMS voltage increases significantly with the rising MA because the SPWM signal's "ON" duration lengthens, keeping the power electronic gates in the "ON" state for longer. Figures 13(a) and 13(b) display the SPWM signal for MA = 0.1 and MA = 0.9, respectively.

For MA greater than 1, the RMS voltage will continue to rise. However, the rate of increase slows down compared to when MA is less than 1. Eventually, the increase halts at a voltage level equal to the input DC voltage. Figure 14 displays the SPWM signal for MA = 2.

Furthermore, the MA also affects the output harmonic content. The total harmonic distortion (THD) of the output decreases as MA increases from 0 to 1. However, when the MA value rises beyond unity, the trend changes. Figure 15 illustrates the outcome of the MATLAB Simulink simulation, indicating that THD values decrease as MA increases until unity, after which they start to increase.

To achieve a high voltage level with minimal harmonic content and facilitate easier filter construction, the MA value should be selected between 0.8 and 0.9. With appropriate filtering, the output voltage can be maintained between 20 and 21 volts for a 24V DC input, with a voltage THD of approximately 38 to 39% for this MA value. Following the filtering process, the voltage THD will further decrease to a very low level.

Simulation Outcome

A MATLAB Simulink simulation of the proposed design was conducted. In this simulation, a step-up transformer with a ratio of 15:230 was used to increase the inverter's output, while the switching frequency was fixed at 10 kHz. Figures 11–14 depict the output of the inverter and the amount of power sent at the leading angle of 45 degrees.

Figure 16 illustrates that after the contactor connects the inverter to the grid, the proposed inverter's current requires approximately two cycles (or 0.04 seconds for a 50 Hz system) to stabilize. This transitional period is caused by the sudden addition of power to the power system, and the magnitude and duration of the transition current depend significantly on the impedance of the power grid.

During the transition period, both real and reactive power experience significant fluctuations. Real power peaks at 75W before stabilizing around 70W, while reactive power overshoots to -32 VAR before stabilizing at -25 VAR. The negative value of reactive power indicates the capacitive feature of the suggested inverter, making it useful for increasing power factor.

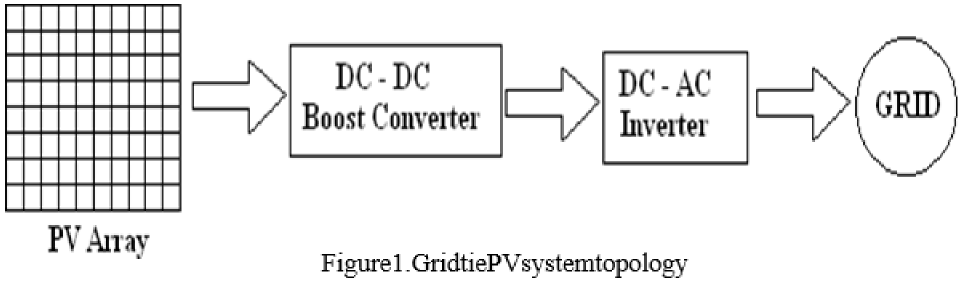


Figure1.GridtiePVsystemtopology

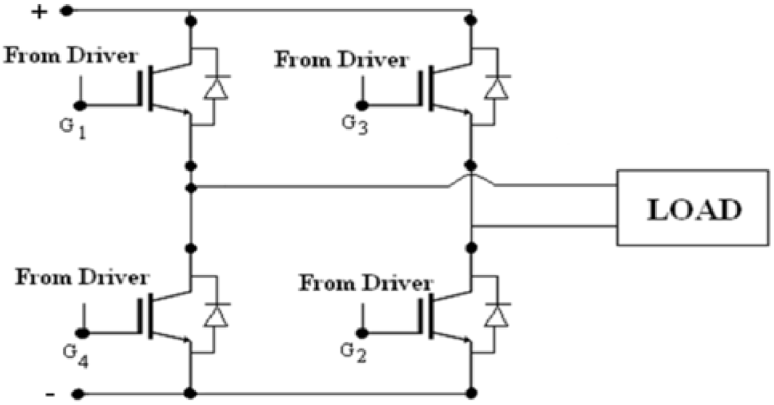


Figure2.Theinverterpower circuit

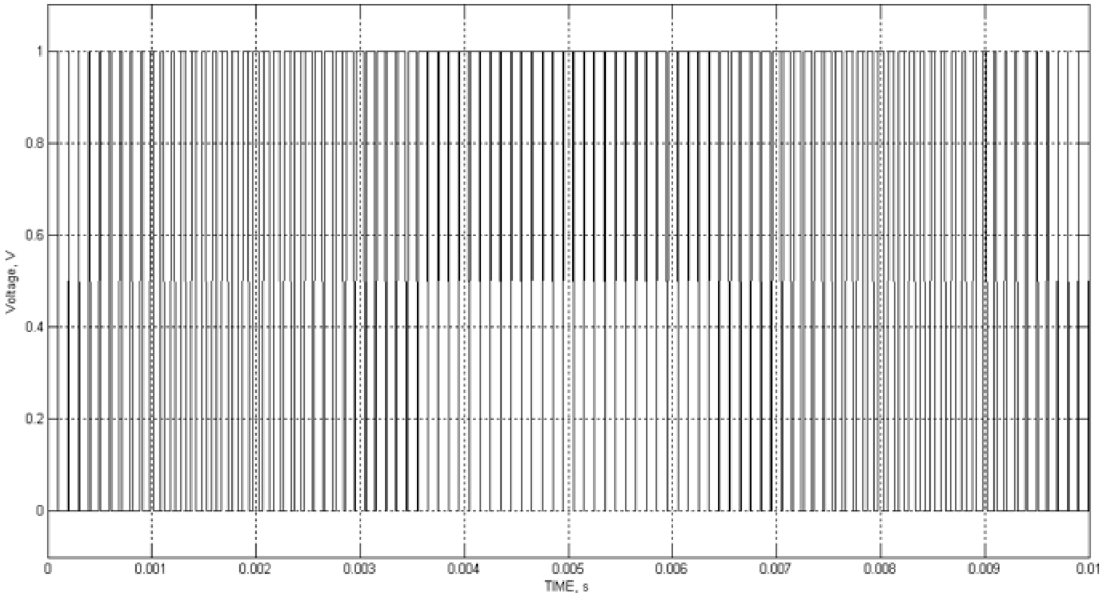


Figure3.The SPWM signal

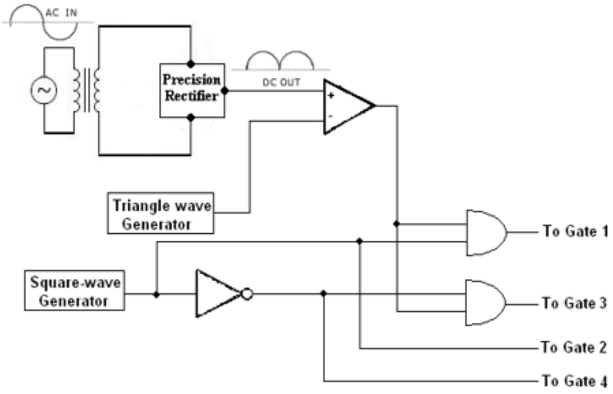


Figure4.Low power control circuit for proposed design

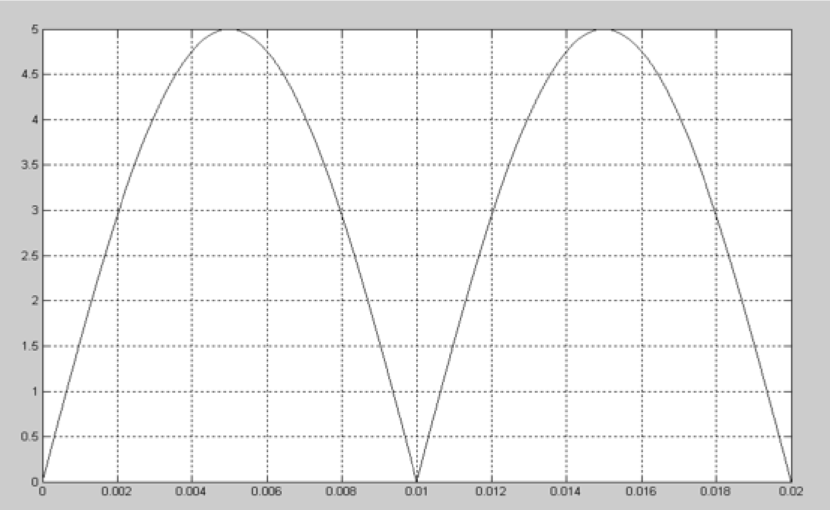


Figure5.Rectifiedsine wave

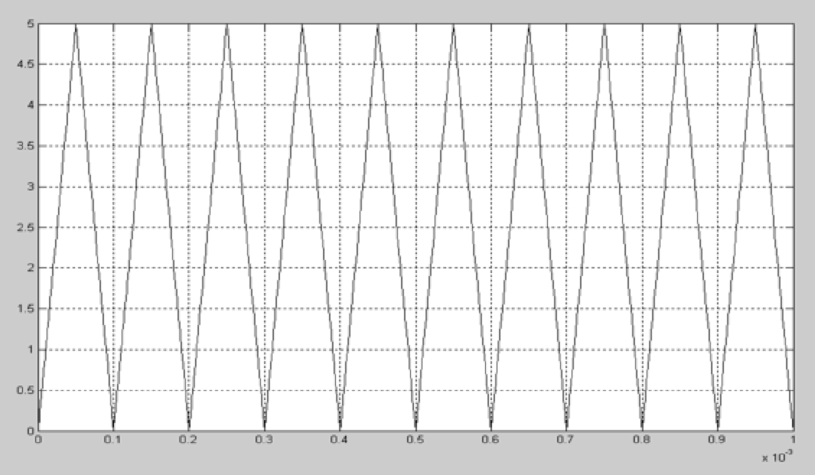


Figure 6. High frequency triangle wave

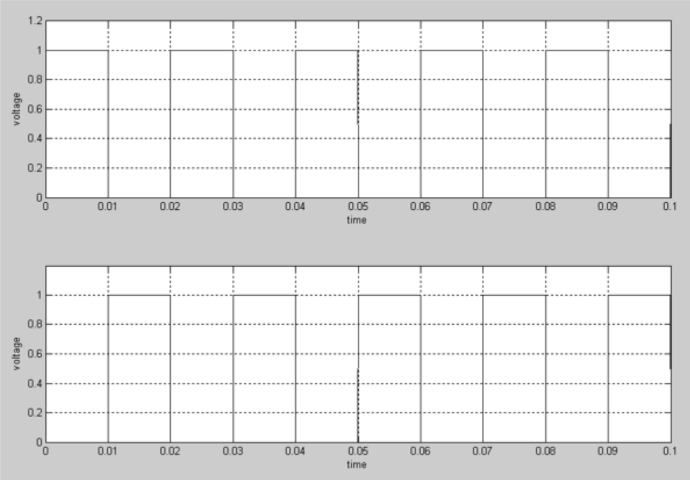


Figure7.Squarewave

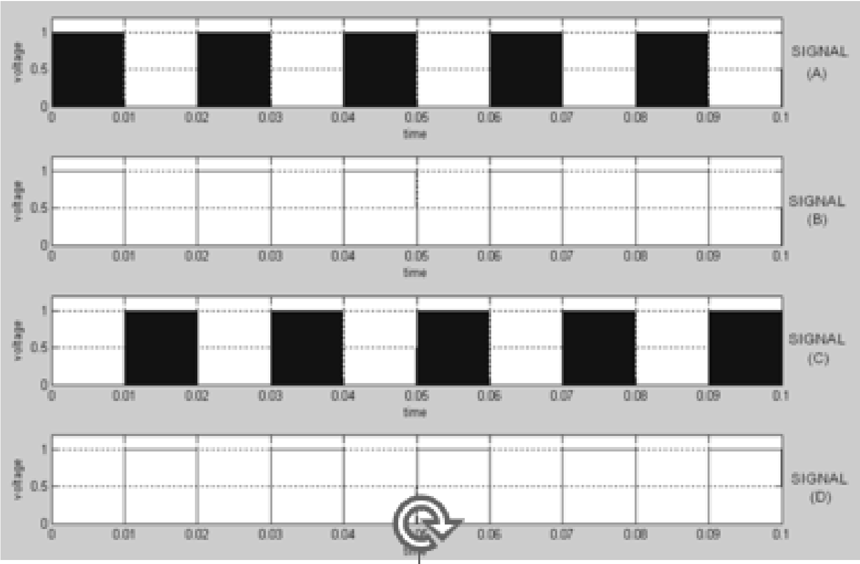


Figure8.Output of the control circuit

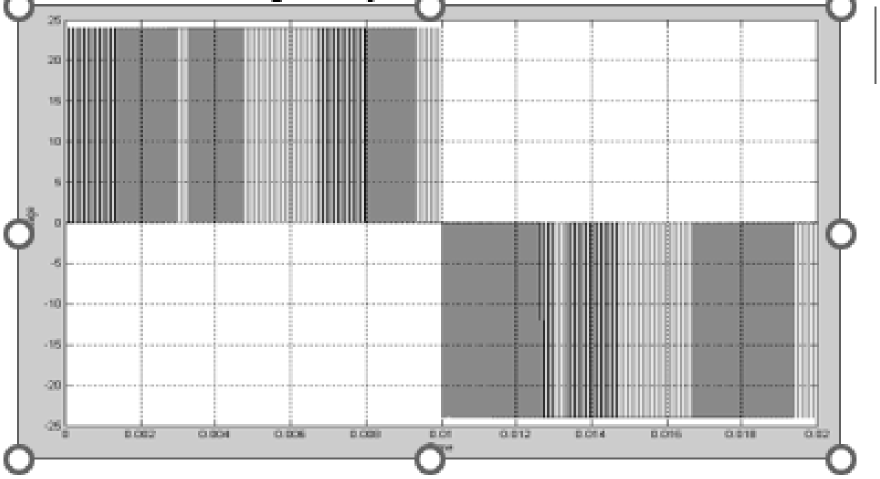


Figure9.Output of the inverter

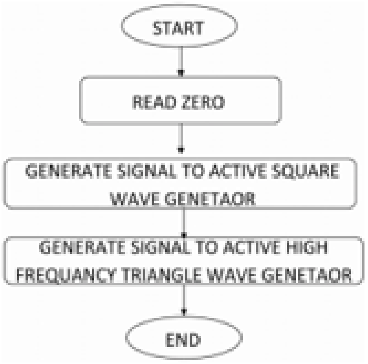
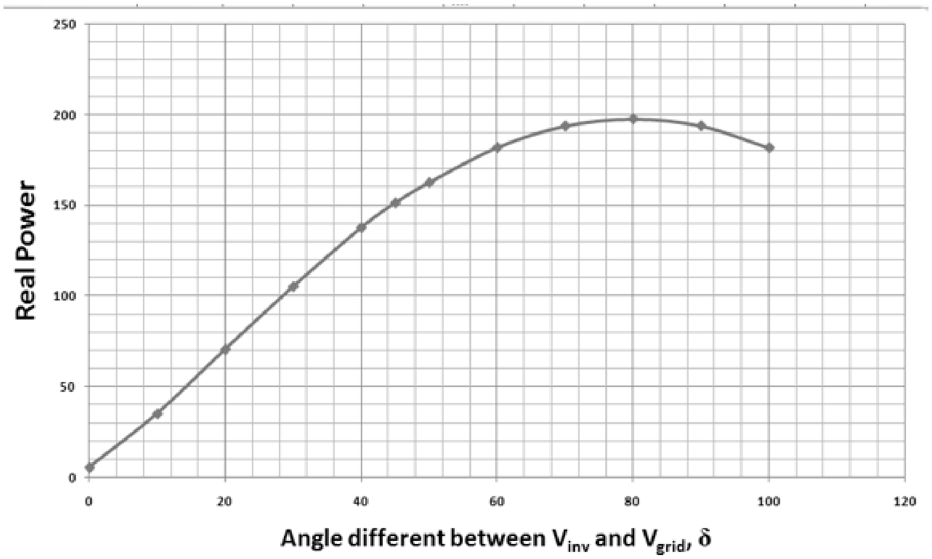


Figure10.Flowchartofthemirco-controller



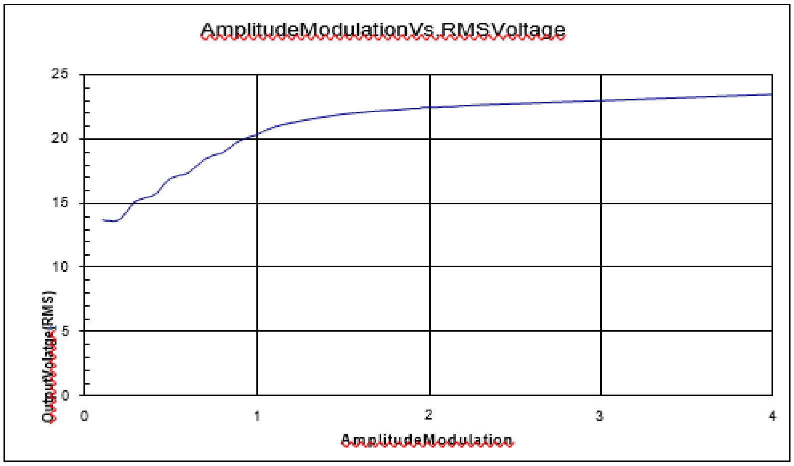
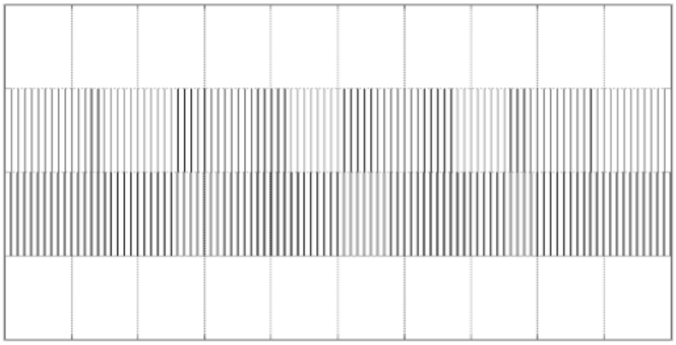


Figure 12: Amplitude Modulation (MA) vs. RMS Voltage



(a)

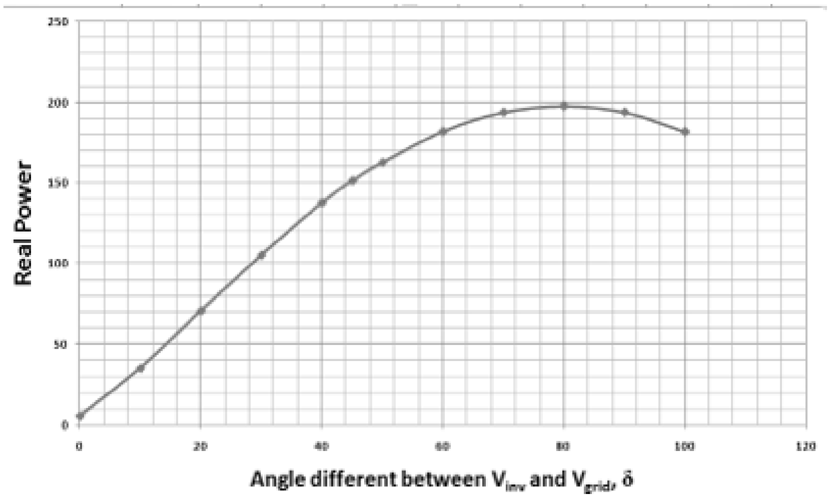


Figure 11 Output real power of the inverter against the angle difference.

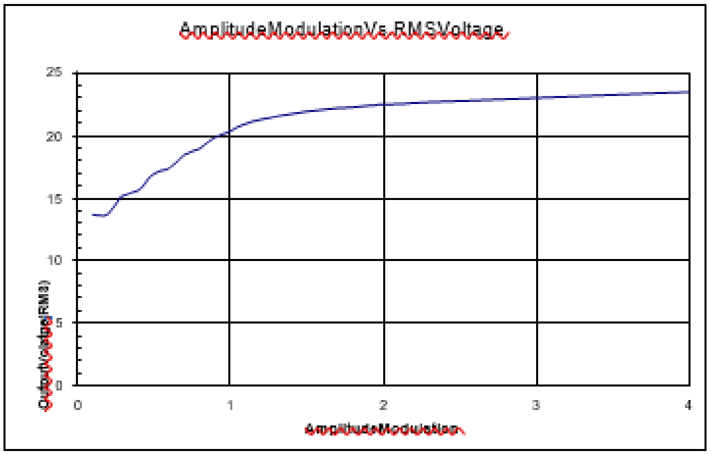
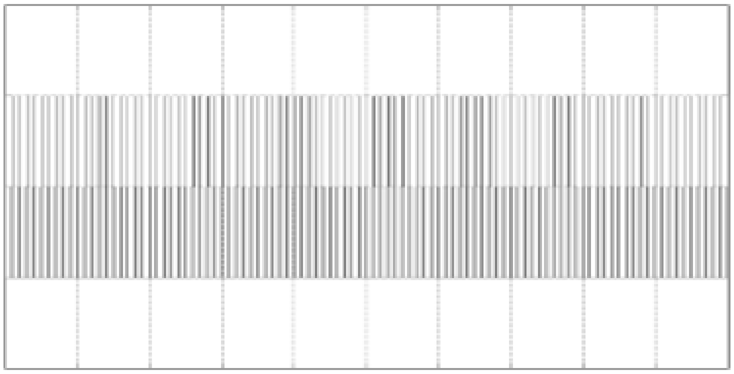
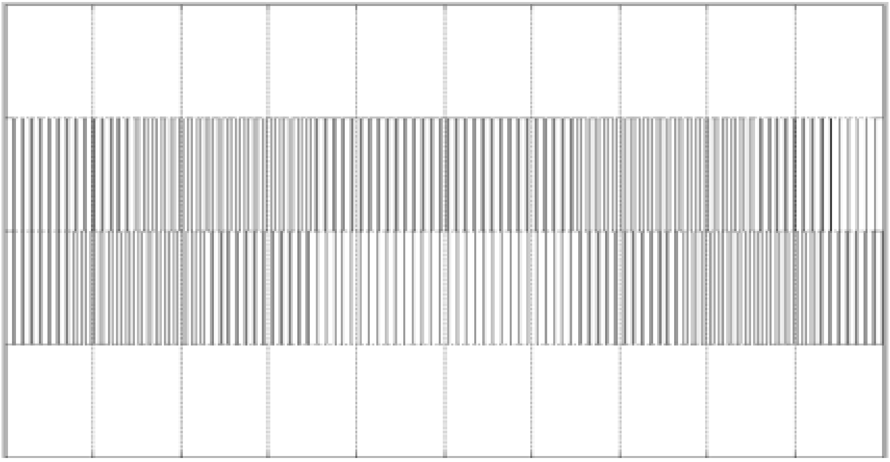


Figure 12: Amplitude Modulation (MA) vs. RMS Voltage



(a)



(b) Figure13.SPWMsignal(a)M_A=0.1 (b)M_A=0.9

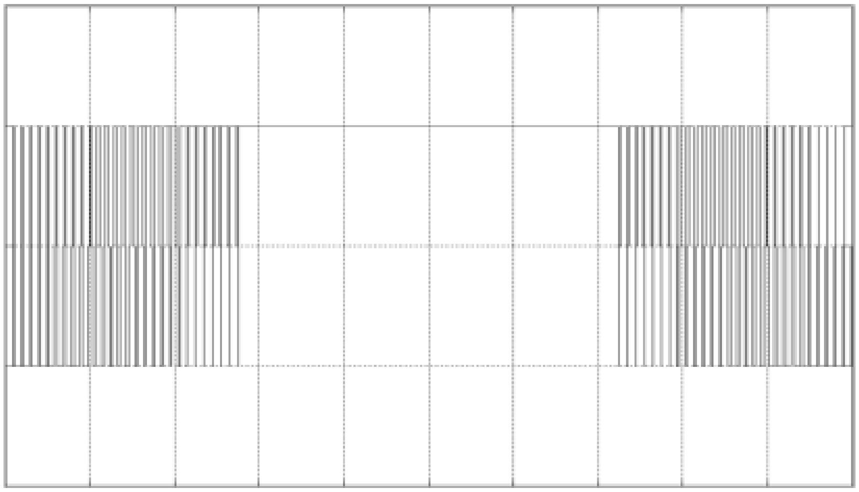


Figure14.SPWMsignalforM_A=2

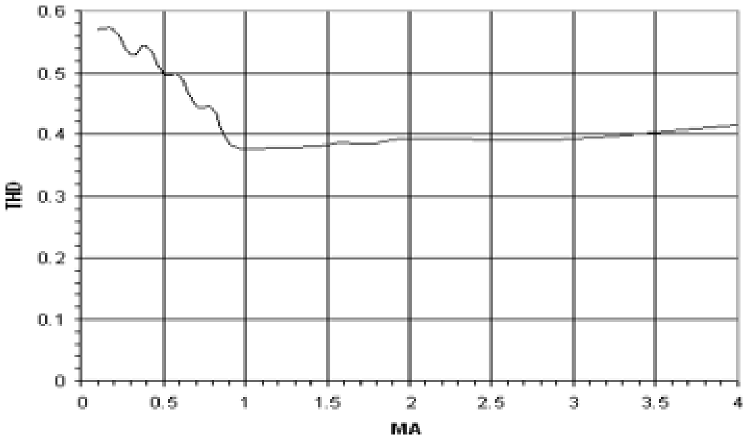


Figure15.AmplitudeModulation$M_A$vs.THD

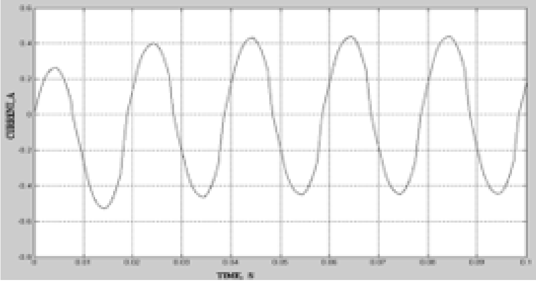


Figure16.Output Current of the inverter

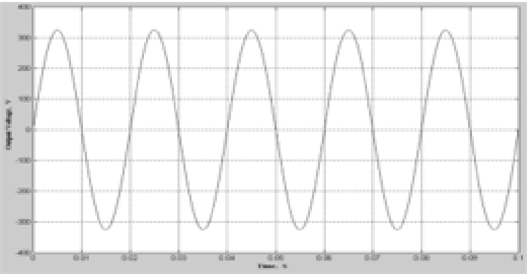


Figure17.OutputVoltageoftheinverter

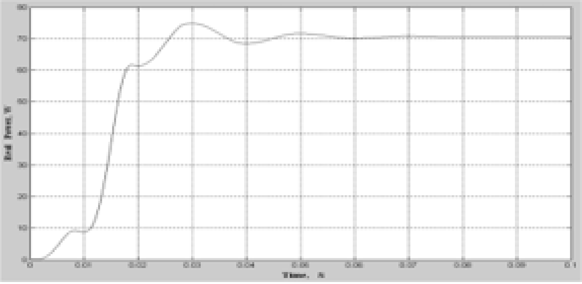


Figure18.OutputRealPowerat[illegible]=45^{0}

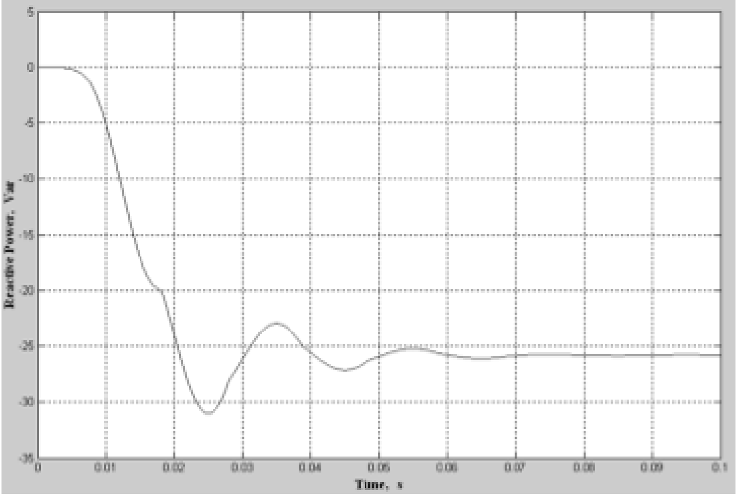


Figure19.OutputReactivePowerat[illegible]=45^{0}

Conclusion

Our study presents a novel switching control approach tailored for a single-phase grid tie inverter, with simulations conducted using MATLAB to emulate grid tie scenarios. The proposed combination switching strategy effectively fulfills the requirements of grid tie conditions, offering an output current to the grid that closely resembles a sine wave.

By integrating both square wave and sinusoidal pulse width modulation (SPWM) signals, our approach optimizes the performance of the grid tie inverter. This hybrid switching method not only enhances the quality of the output voltage but also reduces switching losses across the inverter's switches.

Through MATLAB simulations, we demonstrated that the amplitude modulation (MA) parameter significantly impacts the inverter's output voltage. By varying the MA value, we observed corresponding changes in the RMS voltage, with implications for output voltage regulation and harmonic content.

Moreover, our proposed design incorporates a phase shifter circuit to ensure that the inverter's voltage angle leads that of the grid, facilitating power transmission to the grid. This feature aligns with regulatory standards and enables efficient power transfer while maintaining stability.

The simulation results underscore the effectiveness of our approach, as evidenced by the stable output current achieved after a brief transition period. Despite fluctuations during this transient phase, both real and reactive power settle within acceptable ranges, highlighting the inverter's capability to adapt to grid conditions.

Our study contributes to the advancement of grid tie inverter technology by offering a comprehensive switching control solution that prioritizes grid compatibility, stability, and efficiency. Further research and experimental validation are warranted to validate the proposed approach and explore its potential for practical implementation in renewable energy systems.

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