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INVESTIGATION OF SINUSOIDAL PULSE WIDTH MODULATION (PWM) TECHNIQUES FOR HIGH-POWER GRID-TIED INVERTERS USED IN PHOTOVOLTAIC SYSTEMS

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Abstract: Modern events have shown that the power sector is experiencing diversification as it has never seen before, and using photovoltaic panels is the latest trend in research due to green energy. Some research has been carried out practically and theoretically in the field of pulse width modulation (PWM) techniques for high-power grid-tied inverters used in photovoltaic systems, such as Asma Ben Rhouma (2022) "Sinusoidal pulse width modulation for conventional photovoltaic three-phase inverter", and Mohammed Salem et al. (2022) "Sinusoidal pulse width modulation for multilevel inverters". This paper investigates the capabilities of sinusoidal pulse width modulation techniques for grid-tied power inverters by performing a performance analysis of the system in terms of total harmonic distortion and output current. The MATLAB Simulink software and hardware parameters were used to implement the development and model. The installation of a low-pass filter circuit aids in the creation of cleaner sine waveforms with a 0.17 % total harmonic distortion value. The sinusoidal pulse width modulation (SPWM) approach reduces harmonic distortion by bringing the output voltage closer to that of a genuine sine wave and the reduction of harmonics. MATLAB Simulink software and hardware parameters were used to implement the development and model.

INTRODUCTION

A grid-tied inverter is a power inverter that converts direct current (DC) electricity into alternating current (AC) with the ability to synchronize with an existing utility line. It is useful for transforming direct current (DC) sources of electricity, such as photovoltaic panels, into alternating current (AC) for tying with the grid. Power inverters take direct current power and invert it to alternating current (AC) power so that it can be easily fed into the electric utility company grid. The grid-tied inverter must synchronize its generated frequency of either 50 Hz or 60 Hz with that of the existing grid using oscillator and voltage regulators to ensure that the generated voltage is not higher than the already existing grid voltage (Naresh and Chandra (2018). A well-designed grid-tied inverter has a unity power factor, thus keeping its phase angle within 1% of the alternating current of the grid and having an output voltage and current that is in line with each other (Naresh and Chandra (2018). Unlike traditional grid-connected inverters that use line transformers or old types of frequency transformers to provide galvanic isolation between the grid and photovoltaic panel, modern powered grid-tied inverters use some

technologies, such as high-frequency transformers that use a computerized multistep process to convert power to high-frequency alternating current, conventional low-frequency current, or transformerless inverter design.
Pulse width modulation is a switching technique that controls the pulse width by turning switches between the load and supply. The frequency of the switching process is very fast, and thus does not affect the load. By employing the pulse width modulation technique, the magnitude and frequency of the output voltage can be varied without increasing the number of stages. This makes it possible to eliminate some of the lower order harmonics and reduce the number of filtering circuits needed, leading to an improved output waveform. Pulse width modulation techniques use three forms of modulation: single pulse width modulation, sinusoidal pulse width modulation, and multiple pulse width modulation. Sinusoidal pulse width modulation (SPWM) is a technique used to generate sine wave signals. It is a variation of pulse width modulation (PWM) that involves modulating a triangular waveform with a sine wave with varying amplitude. The output signal appears as a smooth sine wave, similar to an analog signal. The sinusoidal waveform is a mathematical function that describes the oscillation of a quantity over time. The waveform is characterized by its amplitude, frequency, and phase. Sinusoidal pulse width modulation provides an efficient and accurate way of generating sine wave signals (Kavya and Santhoshi (2019)

MATERIALS AND METHODS

The investigation of sinusoidal pulse width modulation techniques for high-power grid-tied inverters used in photovoltaic systems was carried out using MATLAB Simulink. A mathematical model of a photovoltaic system with a high-grid inverter was also developed.

2.1 MODELLING OF THE PV SYSTEM

Photovoltaic modeling in MATLAB can be performed by deriving the function from the equivalent circuit of the PV cell. The PV equivalent circuit is shown in Figure 1.

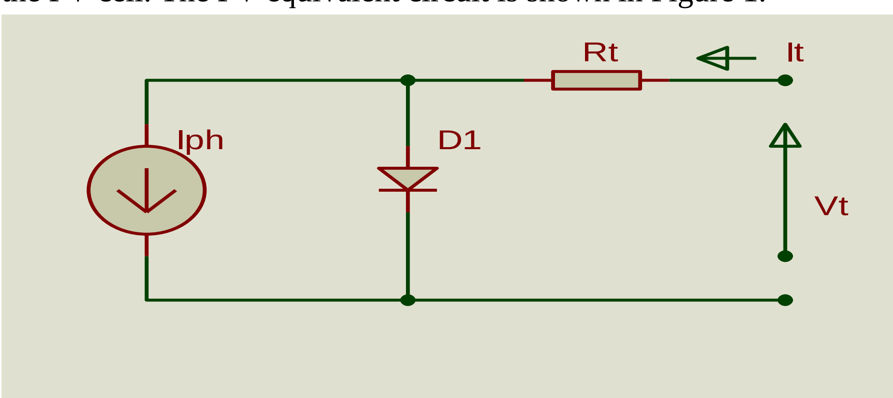

Figure 1. Photovoltaic System in an Array Equivalent circuit
Where;
I_t terminal current,
V_t terminal voltage,
R_t internal resistance,
The relationship between I_t and V_t is represented as;

$$I_t = I_{ph} - I_o \left(e^{\frac{V_t + I_{RS}}{V_{th}}} - 1 \right) \quad (1)$$

Where; I_{ph} is the photocurrent of the module, I_o is the saturation current.
The thermal voltage (V_{th}) of the module is represented as follows:

$$V_{th} = \frac{nNsKT}{q} \quad (2)$$

where n is the ideality factor, Ns is the total number of cells in series, KT is the man constant, and q is the electron charge.
Now, the short circuit voltage V_{oc} and short circuit current I_{sc} of the PV, having a Y_{ss}, X_{ss} as the number of shunts and series of the PV module, will be represented as;

$$I_{pv} = Y_{ss}I_{sc}\left(1 - exp^{\frac{V_{pv} - X_{ss}V_{oc} + \frac{X_{ss}I_{pv}R_s}{Y_{ss}}}{V_{th}X_{ss}}}\right) \quad (3)$$

2.2 MODELLING OF THE PV DC – DC CONVERTER

It is necessary to maintain a constant output voltage irrespective of the irradiance falling on the PV system.

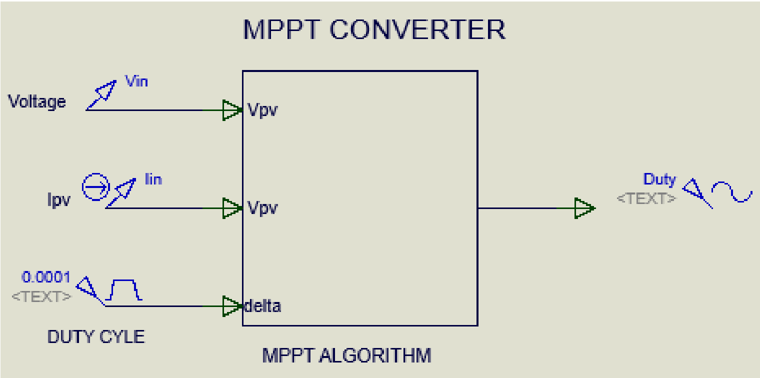

Figure 2. Modeling of the Converter

The maximum power point tracking (MPPT) control technique is commonly used in all DC– DC converters. DC– DC converters are used in PV systems to filter the unregulated, constantly varying, PV output to a required voltage level. The maximum power point tracking algorithm can be derived from the expression that relates the generated power and voltage, which is shown in equation (4).

$$\frac{d_{Ppv}}{d_{Vpv}} = I_{pv} + V_{pv}\frac{d_{Ipv}}{d_{Vpv}} \quad (4)$$

For a DC-DC solar converter, maximum power point tracking (MPPT) algorithms are deployed to extract the maximum power from the PV array. A maximum power point tracking (MPPT) controller is also used to generate a switching pulse for the DC– DC converter, and a constant terminal voltage can be maintained up to a certain level of fluctuation in the input from the PV array.

2.3 MODELLING OF THE INVERTER AND SPWM MODULATOR

Inverters are categorized as half-bridge or full-bridge inverters, depending on the load. Inverters are categorized as pulse width modulation (PWM), multiple pulse width modulation (MPWM), sinusoidal pulse width modulation (SPWM), and multiple sinusoidal pulse width modulation (MSPWM) based on the pulse generator. Inverters use various switching devices, the most common of which are MOSFET and IGBT switches, each with its own set of advantages and disadvantages.
The sinusoidal pulse width modulation (SPWM) approach reduces harmonic distortion by bringing the output voltage closer to that of a genuine sine wave and reducing harmonics. MATLAB Simulink software and hardware parameters were used to implement the development and model.

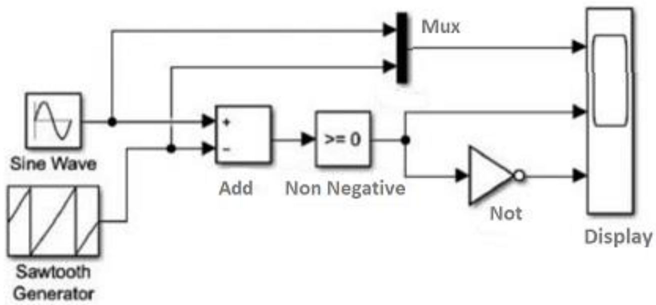

Figure 3. Simulation of Digital Signals in Matlab/Simulink

SPWM is obtained from a controller by comparing a sinusoidal wave with a triangular wave. Figure 3 shows the MATLAB/Simulink-designed SPWM generator.

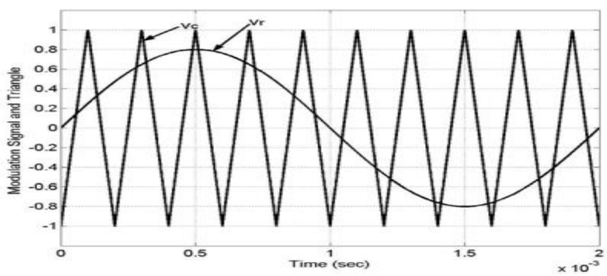

Figure 4. SPWM Signal Curve

As shown in Figure 4, to obtain small dimensions and fine sinusoidal output of dc/ac converters, high-resolution sinusoidal pulse-width modulation (SPWM) switching is necessary. The pulse wave generated is shown in Figure 3.6, which shows the sinusoidal waveform (V_c) and triangular waveform (V_r). The amplitude of the triangular wave (V_r) is generally kept constant

The modulation index (M_i) controls the harmonic content of the voltage output and is given by

$$M_i = \frac{V_r}{V_c} \quad (5)$$

The frequency modulation is given by

$$M_f = \frac{f_1}{f_c} \quad (6)$$

The concept of pulse width modulation (PWM) for inverters is described with analyses extended to different types of PWM strategies.

2.4 HALF-BRIDGE INVERTER MODELLING

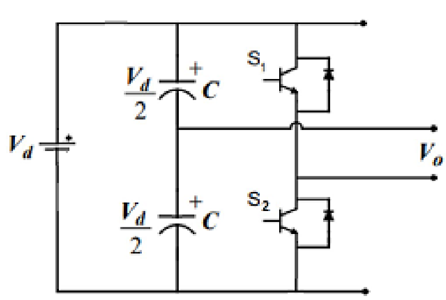

Figure 5. Half-bridge circuit diagram of the sinusoidal pulse width modulation inverter

The PWM scheme depicted in Figure 4, where V_c is the peak value of the triangular carrier wave and V_r modulating signal. It shows the triangle and the modulation signal with some arbitrary frequency and magnitude. To obtain the SPWM, a high-frequency triangular carrier wave is compared with a sinusoidal reference of the desired frequency. The intersection of V_r and V_r waves determines the switching instants and commutation of the modulated pulse.

As shown in Figure 5, the switches S_1 and S_2 are controlled by contrasting the control signal and the triangular wave, which are mixed in a comparator given as follows:

$V_{out} = \frac{V_d}{2}$ (7)

When the sinusoidal wave V_r has a magnitude higher than the triangular wave V_c, the comparator output is high and denoted as;

$$V_r > V_c$$

S_1 is ON, $V_{out} = \frac{V_d}{2}$ (8)

When the sinusoidal wave V_r has a magnitude lower than the triangular wave V_c, the comparator output is high and denoted as;

$$V_r < V_c$$

S_2 is ON, $V_{out} = -\frac{V_d}{2}$ (8)

From Kirchhoff's voltage law (KVL), the switches on the same side are not turned on at the same time,

$S_1 + S_2 = 1$ (9)

Equation (4) gives the condition for each side of the inverter circuit and enables the voltage to move between $\frac{V_d}{2}$ and $-\frac{V_d}{2}$ for any given voltage.

2.5 FULL-BRIDGE INVERTER MODELLING

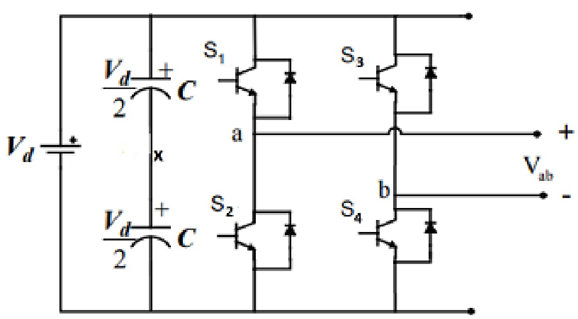

Figure 6. Full Bridge Circuit Diagram of the Sinusoidal Pulse Width Modulation Inverter

The output voltages V_{ax} and V_{bx} are the phases from A and B that meet at a point, say x. V_{no} is the neutral voltage between point x and the DC midpoint.

$V_{ab} = V_{an} - V_{bn}$ (10)

Using KVL,

$\frac{V_d}{2}(S_1 - S_2) = V_{an} + V_{nx} = V_{ax}$ (11)

$\frac{V_d}{2}(S_3 - S_4) = V_{bn} + V_{nx} = V_{bx}$ (12)

The switching function is approximated by the Fourier transform series and is given as

$$\frac{1}{2}(1 + M) \quad (13)$$

Where M is the modulating signal function, which gives the switching pulses, when compared with the triangular waveform. Hence, from equation (5) and (6), M will be represented as;

$$M_1 = \frac{2(V_{ax} + V_{xo})}{V_d} \quad (14)$$

$$M_2 = \frac{2(V_{bx} + V_{xo})}{V_d} \quad (15)$$

Equation (11) and (12) represent the general expression for deriving modulation signals for different modulation schemes by assigning the required values for the output voltages and neutral voltages, respectively.

2.6 UNIPOLAR INVERTER SPWM MODELLING

In the unipolar modulation scheme, the components on one side are turned ON or OFF based on the comparison of the modulation signal V_r with a high-frequency triangular wave V_c. The components on the other side are turned ON or OFF by comparing the modulation signal V_r, with the same high-frequency triangular wave V_c.

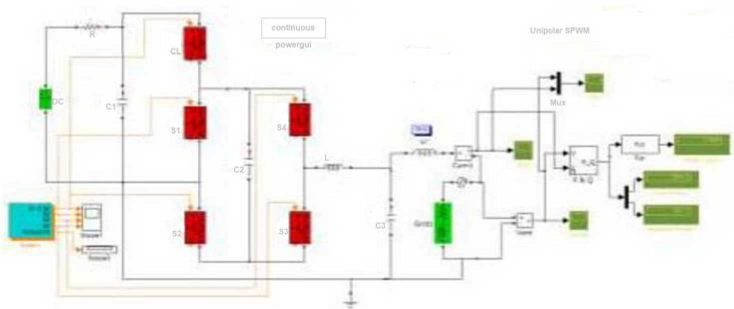

Figure 7. Unipolar sinusoidal pulse width modulation inverter

Figure 7 shows the phase voltages, line-to-line voltages, and load current obtained from a unipolar PWM scheme. Given an RL load of R = 10Ω and L = 0.1H, C1 = C2 = 10uf. The dc voltage is 500 V and the switching frequency is 10 kHz. The modulation signal M has a magnitude of 0.8. The unipolar scheme for a single - phase full bridge inverter drawn in MATLAB, with the modulation signals for one side of the components and the required comparison to yield switching pulses on both sides of components S_1 and S_2. The switching on the other side of the components is obtained as

$$S_3 = 1 \;\; S_1 \quad (16)$$

$$S_4 = 1 - S_2 \quad (17)$$

The switching logic for the modulation signal on each side of the components simulated is as follows:

The side connected to A when the sinusoidal wave V_r has a magnitude lower or higher than the triangular wave V_c.

$V_r > V_c$: S_1 is ON, $V_{ax} = \frac{V_d}{2}$ (18)

$V_r < V_c$: S_1 is ON, $V_{ax} = -\frac{V_d}{2}$ (19)

The side connected to B when the sinusoidal wave V_r has a magnitude lower or higher than the triangular wave V_c.

$V_r > V_c$: S_2 is ON, $V_{bx} = \frac{V_d}{2}$ (20)

$V_r < V_c$: S_2 is ON, $V_{ax} = -\frac{V_d}{2}$ (21)

From the unipolar switching modulation technique, the output voltage level changes from 0 to V or from 0 to +V. This scheme effectively doubles the switching frequency as far as the output harmonics are concerned compared to the bipolar switching scheme.

2.7 BIPOLAR INVERTER SPWM MODELLING

In bipolar inverter sinusoidal pulse width modulation**,** the diagonally opposite components S1, S4, S2, and S3 are turned ON or OFF simultaneously. The output of side A is equal to and opposite to the output of side B.

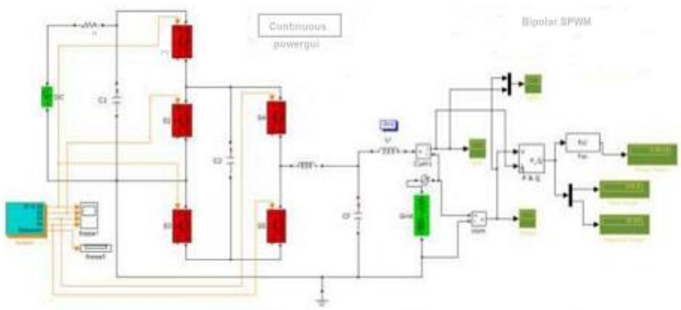

Figure 8. Bipolar sinusoidal pulse width modulation inverter

Figure 8 shows the modulation signal, output voltage, and load current for bipolar modulation SPWM on a single-phase inverter full bridge as depicted in Matlab, with an RL load of 10 and 0.1 H, 500 V voltage. The output voltage is determined by comparing the control signal V_r and the triangular signal V_c, to get the switching pulses for the components. The switching pattern is as follows:

$V_r > V_c$: S_1 is ON, $V_{ax} = \frac{V_d}{2}$ (22)

$V_r < V_c$: S_3 is ON, $V_{bx} = -\frac{V_d}{2}$ (23)

The side connected to B when the sinusoidal wave V_r has a magnitude lower or higher than the triangular wave V_c.

$V_r > V_c$: S_2 is ON, $V_{ax} = -\frac{V_d}{2}$ (24)

$V_r < V_c$: S_4 is ON, $V_{bx} = \frac{V_d}{2}$ (25)

From equation (22) and (24)

V_{bx} (t) = - V_{ax} (t) (26)

Therefore, the line-to-line output voltage is given as;

V_{ab} (t)=V_{ax} (t)-V_{bx} (t)=2V_{ax} (t) (27)

Because the voltage components switch between two levels V_d and - V_d , the modulation technique is known as bipolar sinusoidal pulse width modulation or double sinusoidal pulse width modulation.

2.8 LOW-PASS FILTER

A low-pass filter (LPF) is a circuit that only passes signals below its cutoff frequency while attenuating all signals above it. It complements a high-pass filter, which only passes signals above its cutoff frequency and attenuates all signals below it.

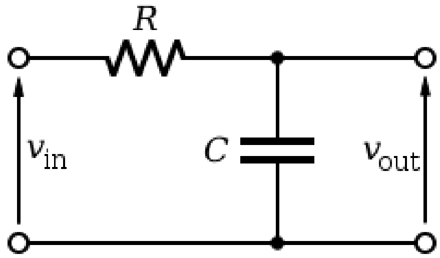

Figure 9. Low-pass filter circuit

SIMULATION AND ANALYSIS

3.1 SIMULATION

The simulation was performed using MATLAB Simulink, and the implementation of sinusoidal pulse width modulation is presented in Figure 10.

Here, the triangular carrier signal V_c of the switching frequency is compared with the sinusoidal reference signal V_c, and the control pulses are obtained for the positive and negative cycles of the sequence. The simulation output voltage of the SPWM is shown in Figure 13. The operation of the single-phase full bridge inverter for positive output load voltage is obtained by the conduction of the field effect transistors (FETs), S1 and S2 for the positive half cycle of the PV input, and S3 and S4 for the negative half cycle of the PV input. The experimental results for the sinusoidal pulse width modulation are tested in simulation with the component specifications outlined in Table 1.

Table 1 Specifications of the components used for sinusoidal pulse width modulation

Description	Values	Symbols
Rated input frequency	5	Hz
Rated output frequency	50	Hz
Rated PV input voltage (VOC)	300	V
Rated PV input current (Isc)	200	A
Rated power	500	KVA
Resistance	10	Ω
Rated capacitance	10	pF
Rated irradiance	900	W/m^2
Rated Inductance	0.12	H

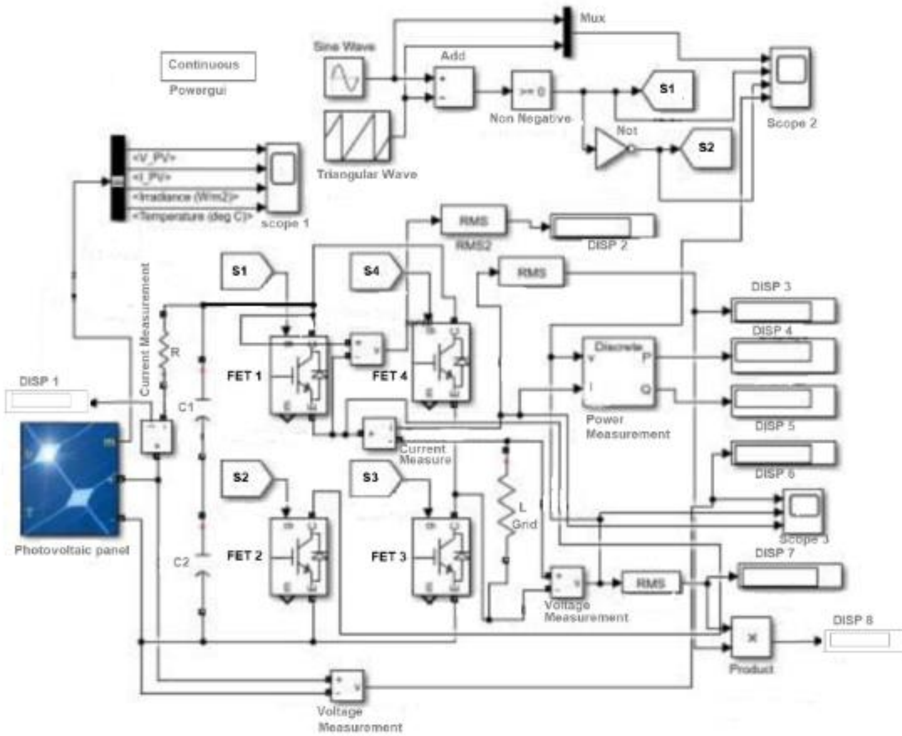

Figure 10 PV System with Power Inverter using the SPWM technique

Figure 9 shows the PV system coupled with the power inverter design with the FET done in MATLAB Simulink software. A single-phase full bridge inverter with an FET is designed and simulated. The inverter switches are controlled by sinusoidal pulse width modulation control signals, and a resistive load is connected across the inverter output, acting as the grid.

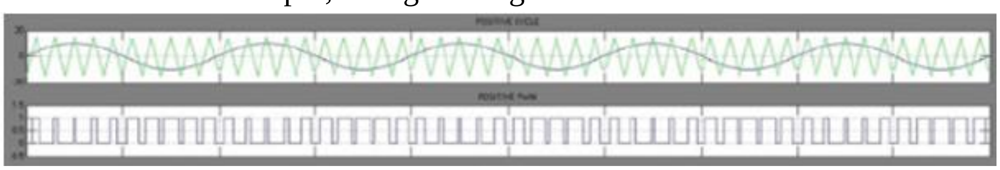

Figure 11 Positive Cycle and Positive Pulse of the SPWM Signal

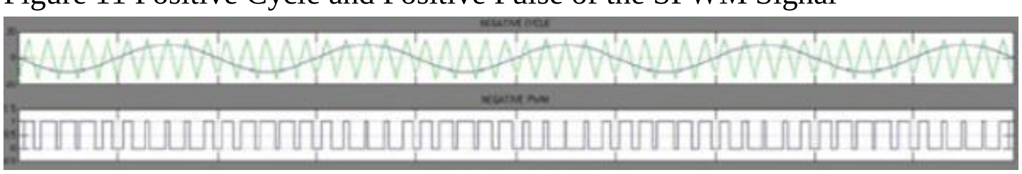

Figure 12 Negative Cycle and Negative Pulse of the SPWM Signal

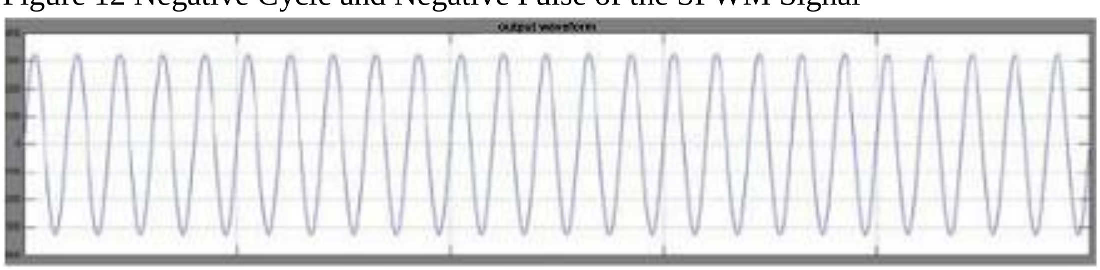

Figure 13 Output Waveform

Table 2 SPWM FET switching states

Sequence from the supply	Sequence of switching	Operation mode	Grid utility
Positive pulse	S1 and S3	Full bridge SPWM mode	Resistive grid load
Negative pulse	S2 and S4	Full bridge SPWM mode	Resistive grid load
Positive pulse	S2 and S4	Full bridge SPWM mode	Resistive grid load
Negative Pulse	S1 and S3	Full bridge SPWM mode	Resistive grid load

3.2 RESULT ANALYSIS

The maximum power point tracking converter is implemented as the PV input voltage converter in MATLAB Simulink with direct current as the supply input to the DC–DC converter. When the control signals from the SPWM generator are given to the FET switches S1 and S2 for the positive half-cycle of the input PV voltage, the direct current output is obtained in the positive potential, as shown in Figure 12. Again, when the control signals from the SPWM generator are given to the FET switches S3 and S4 for the negative half cycle of the input PV voltage, the direct current output is obtained in the negative potential, as shown in figure 13. This negative load voltage serves as the resistive load acting as the grid output. Alternating current output is achieved by a change in the modulation index M, as given in Equation 14 and 15, with control pulses through SPWM for the positive and negative cycles of the direct current input,, respectively. The switching states of the FET are presented in Table 2.

The output frequency of the MPPT converter when working with the PV and inverter is of the necessary value depending on the developed SPWM cycle frequency in which the output frequency is 50 Hz for an input of 5 kHz DC supply, as shown in Figure 14. The output waveform shows an increase in the voltage output of about 325 V from an input voltage of 300 V with an optimum irradiance of 900w/m^2 from the sun, thereby leading to an increase in power with minimum losses and improving the inverter efficiency. The installation of a low-pass filter circuit aids in the creation of cleaner sine waveforms with 0.17% total harmonic distortion. The required reference signal as a feed forward signal for sinusoidal pulse width modulation (SPWM) control is generated by a sophisticated digital signal processor in traditional grid-connected inverters. However, as the alternating current mains varies, the reference signal must be recalculated to maintain the required power management. It increases the controller's processing overhead and has become a major roadblock for grid-connected energy storage systems that require power flow regulation.

CONCLUSION

The sinusoidal pulse width modulation (SPWM) approach reduces harmonic distortion by bringing the output voltage closer to that of a genuine sine wave and reducing harmonics. MATLAB Simulink software and hardware parameters were used to implement the development and model. The installation of a low-pass filter circuit aids in the creation of cleaner sine waveforms with 0.17% total harmonic distortion. The required reference signal as a feed forward signal for sinusoidal pulse width modulation (SPWM) control is generated by a sophisticated digital signal processor in traditional grid-connected inverters. However, as the alternating current mains varies, the reference signal must be recalculated to maintain the required power management. It increases the controller's processing overhead and has become a major roadblock for grid-connected energy storage systems that require power flow regulation. The sinusoidal pulse width modulation technique can be used to improve the power quality of the output and manage uncertainties compared with other methods. This study has contributed to knowledge by enhancing energy conversion and seamless grid integration.

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