Three-phase PWM inverter with RL load

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***Abstract*—The conversion of direct current (DC) to alternating current (AC) is pivotal for interfacing with resistor-inductor (RL) loads. This project explores the design and performance analysis of two prominent inverter types: square-wave and three-phase Pulse Width Modulation (PWM) inverters, in meeting specific technical criteria. Square-wave inverters, characterized by abrupt voltage transitions, offer simplicity but introduce harmonic distortions, particularly noticeable in RL loads. Meanwhile, three-phase PWM inverters provide smoother waveforms by finely adjusting output, resulting in reduced harmonics and improved efficiency with RL loads. This project entails the construction of Simulink models and circuits to fulfil the technical requirements and investigates the effects of varying modulation indices and inductance on output waveforms. Additionally, it compares the performance of PWM and square-wave inverters, considering factors such as complexity, cost, waveform quality, and efficiency.**

***Index Terms*—Square-wave inverters, Pulse Width Modulation (PWM) inverters, Resistor-inductor (RL) loads, Simulink modeling, Harmonic distortion**

I. Introduction

In this project, we focus on the design and analysis of three-phase Pulse Width Modulation (PWM) inverters, which finely adjust the output voltage to produce smoother waveforms with reduced harmonic content compared to traditional inverters. Through constructing Simulink models and circuits and investigating the effects of modulation indices and inductance on output waveforms, we aim to understand the performance characteristics of PWM inverters comprehensively. Additionally, a comparative analysis between PWM and square-wave inverters will be conducted, considering factors such as complexity, cost, waveform quality, and efficiency. This project contributes to advancing our understanding of PWM inverter design and its suitability for various power electronics applications involving RL loads.

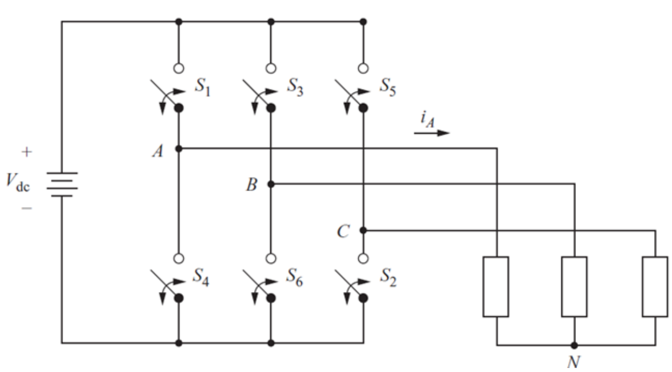


Fig. 1. Three-phase PWM inverter with RL load topology

II. Requirements and Theory

A. Requirements

The final design of the circuit was required to meet the following criteria:

- $V_{dc} = 250$ V
- $f = 50$ Hz
- $m_a = 0.8$
- $m_f = 17$
- $R = 8\ \Omega$
- $L = 30$ mH

B. Theory and Equations

The main job of inverters in power electronics is to change direct current (DC) into alternating current (AC). This change is very important for working with RL (resistor-inductor) loads. There are two main types of inverters for this: square-wave inverters and three-phase Pulse Width Modulation (PWM) inverters.(1) Each type has its own advantages and disadvantages depending on the situation.

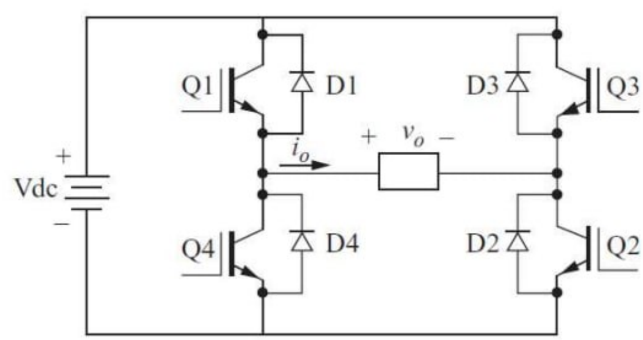


Fig. 2. Square Wave Inverter

Square-Wave Inverter with RL Load (2): Square-wave inverters change DC into AC with sharp changes between high and low voltage. This makes them simple to design and control. When used with an RL load, the sudden voltage changes create harmonics, or extra waves, that are measured by the THD formula:

$$\text{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} (V_{n,\text{rms}})^2}}{V_{1,\text{rms}}} \tag{1}$$

These harmonics are somewhat reduced by the load's inductance. Although these inverters are good for situations needing low cost and simple design, they can cause more distortion and problems with the load.

Three-Phase PWM Inverter with RL Load: On the other hand, three-phase PWM inverters adjust their output more carefully, creating a waveform that looks more like a smooth wave. This method reduces harmonics and improves power efficiency to RL loads. The control of this inverter's output is managed by the modulation indices, m_f and m_a, which are:

$$m_f = \frac{f_{\text{carrier}}}{f_{\text{reference}}} \tag{2}$$

$$m_a = \frac{V_{m,\text{reference}}}{V_{m,\text{carrier}}} \tag{3}$$

These indices control the output's frequency and volume, especially m_a, which directly affects the main wave component of the output voltage:

$$V_1 = m_a V_{\text{dc}} \tag{4}$$

This allows for better performance control and greatly improves how the inverter works with RL loads.

Comparative Analysis: While the square-wave inverter is simpler, this simplicity can lead to more distortion when used with RL loads. The three-phase PWM inverter, with its detailed output control, fits better with RL loads, making it the better choice for situations where wave quality and power efficiency are very important. The decision on which inverter to use depends on the specific needs of the application, considering things like complexity, cost, and the need for accurate wave quality and efficiency.

III. Simulink Model Design

A. Simulink Model Overview

The Simulink model (Fig. 3) is designed to simulate a PWM inverter that converts a DC input into an AC output with adjustable frequency and amplitude, commonly used in power electronics applications. The Simulink model consists of the following components:

- DC Source: There is a single DC source that provides the input power for the inverter circuit.
- Switches: The model includes six semiconductor devices, configured in a three-phase bridge topology to form the core of the PWM inverter.
- Gate Pulse Generators: The gate pulses for the inverter switches are generated by a control system that includes PWM generators, ensuring the creation of appropriate gating signals for the transistors.
- Control System: The control system incorporates a block that handles the three-phase (abc) signal and a carrier (triangular wave) signal generator comparing them to produce a PWM signal to open or close the switches
- Resistive and Inductive Loads: The model includes both resistive and inductive elements on the AC side.
- Visualization Tool: The THD analysis block is connected to a display component, which allows for real-time visualization of the total harmonic distortion in the inverter's output.

IV. Discussion

A. Experiments with PWM Inverter

Standard parameters for PWM Inverter are as follows:

- $V_{dc} = 250$ V
- $f = 50$ Hz
- $m_a = 0.8$
- $m_f = 17$
- $R = 8\ \Omega$
- $L = 30$ mH

These standard parameters are kept constant while we change particular parameters such as m_f, m_a and L one by one to analyse how each parameter influences the output current signal of the circuit.

1) m_f changes: We observe that when we change m_f parameter (Table I), the amplitude of the current signal does not change though some little variations are seen. These variations are due to harmonics. The major change is observed in total harmonic distortion (THD) of the current signal. As we kept increasing the m_f parameter the THD of the signal kept decreasing. For example, the current signal did not look like a sinusoid signal when we configured m_f to be 3 (Figure 10). Here, we can conclude that the THD of a signal is highly impacted by m_f parameter.

2) m_a changes: While m_a increases (Table II), We observe that THD decreases and the magnitudes of the harmonics decrease as well. The magnitude of the current signal or the peak-to-peak current, 2 times the magnitude, increases. This tells us that in order for the output signal to look more like ideal sinusoidal signal, we need to increase the m_a parameter. The maximum value of m_a is 1.

3) L changes: With regard to the parameter L, each time L increases THD of the output signal decreases and the magnitude also decreases. In other words, L impacts the value of the magnitude of each harmonic and the power absorbed by a load.

B. Comparing the PWM inverter and the square wave inverter

1) PWM Inverter: Our goal was to design the PWM inverter based on the design requirements mentioned above. While R and L values are known and can be easily used in our Simulink model, the m_a and m_f parameters were used to configure the individual parameters of reference sinusoid and triangular wave (carrier signal). The magnitude of the carrier signal is always the same as the DC power supply voltage, whereas the magnitude of the reference sinusoid signal is $V_{DC} \times m_a$. With regard to the frequencies of each wave signal, the frequency of the reference sinusoid signal is always 50Hz and the frequency of the triangular wave signal is $m_f \times 50Hz$. Comparing the reference and carrier signals we can open and close the switches. When we simulated the circuit in simulink, we found out that using these design requirements the output signal becomes the sinusoid with the THD 7.18% (Figure 7). The output signal can be seen from Figure 5

2) Square wave inverter: Using the same design requirements as in designing of PWM inverter except m_a and m_f We had the output signal depicted in Figure 6. When simulating the square wave inverter, we used the pulse generator with frequency 50Hz and the duty cycle of 50% to open and close the Q1Q2 and Q4Q3 pair of switches (Figure 2). The THD of the output current signal of this circuit is found to be 14.19% (Figure 8). If we compare the PWM and square wave inverter, we can conclude that the THD value of the PWM inverter is almost twice less than that of the square inverter. Thus, the PWM inverter generates a more ideal sinusoid output signal rather than the square wave inverter. However, the control of the PWM inverter is more complex and it requires more components than the square wave inverter.

REFERENCES

V. APPENDIX

TABLE I
THE VALUES OF THD AND PEAK-TO-PEAK CURRENT VALUES WHEN m_f CHANGES

mf	3	7	13	17	23	27
THD	62%	17.70%	9.40%	7.18%	5.30%	4.50%
Current, peak-to-peak	14.1	15.28	14.86	14.7	14.8	14.75

TABLE II
THE VALUES OF THD AND PEAK-TO-PEAK CURRENT VALUES WHEN m_a CHANGES

ma	0.1	0.3	0.5	0.7	0.9	1
THD	74.43%	24.10%	13.55%	8.70%	6%	5.20%
Current, Peak-to-peak	3.37	6.7	9.95	13.14	16.3	18.13

TABLE III
THE VALUES OF THD AND PEAK-TO-PEAK CURRENT VALUES WHEN L CHANGES

L	1mH	5mH	20mH	40mH	60mH	120mH
THD	83.50%	27.40%	8.80%	6.50%	6%	5.60%
Current, Peak-to-peak	40.4	29	18.2	12.6	9.5	5.46

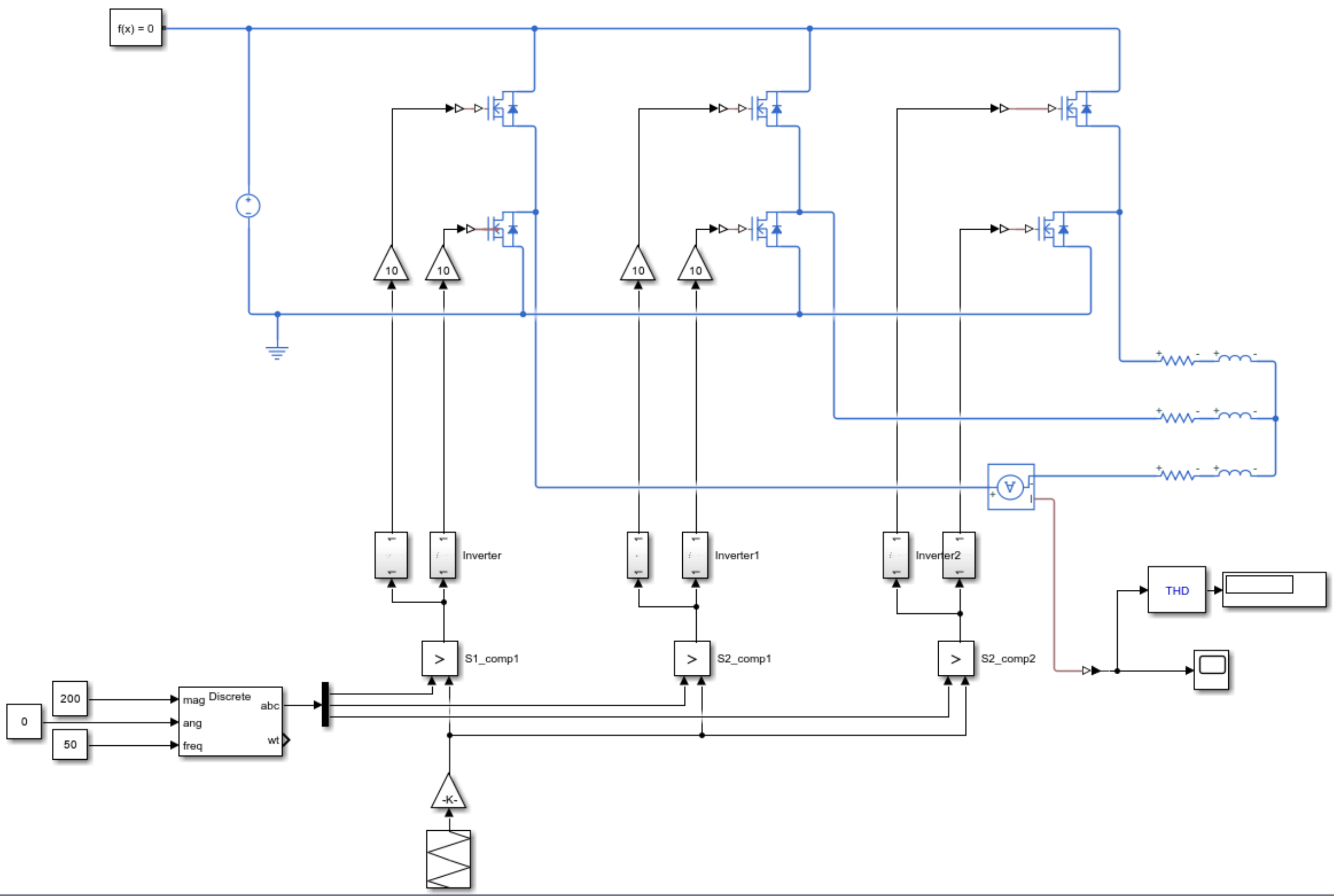


Fig. 3. Simulink model design of the PWM inverter

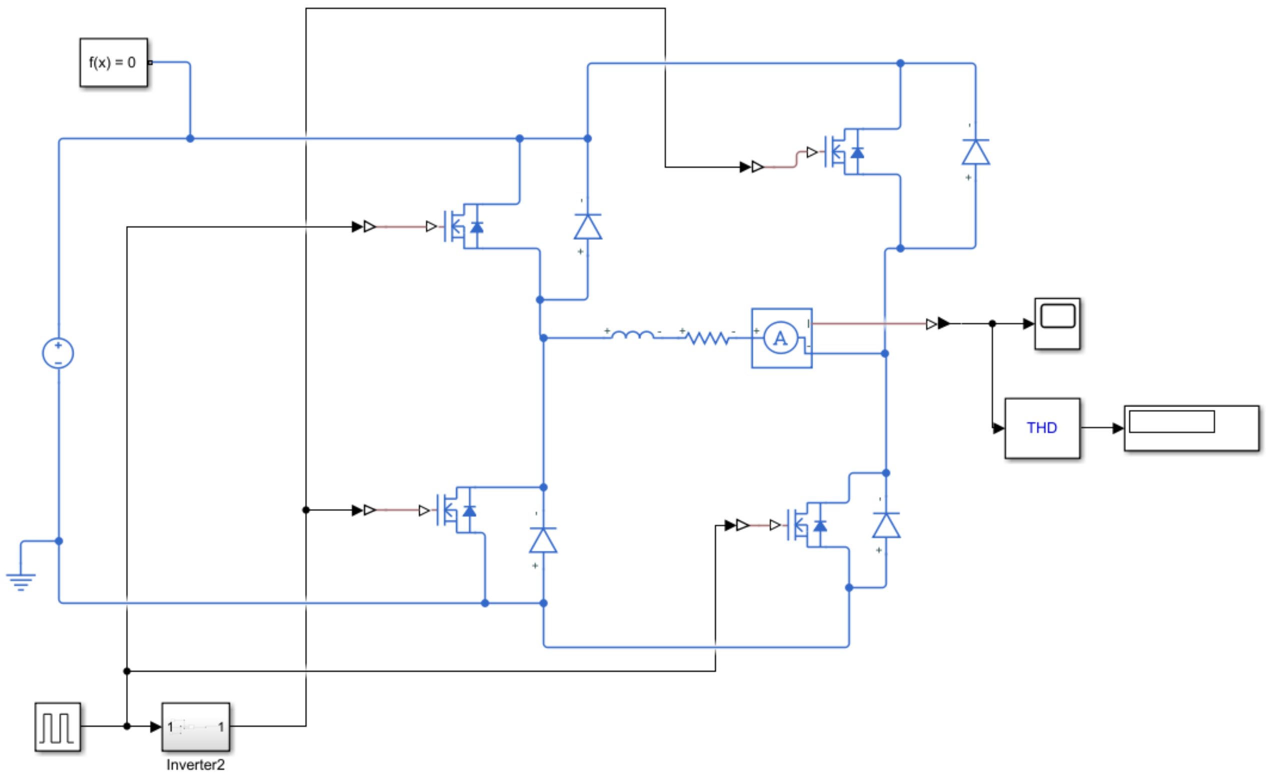


Fig. 4. Simulink model design of the square wave inverter

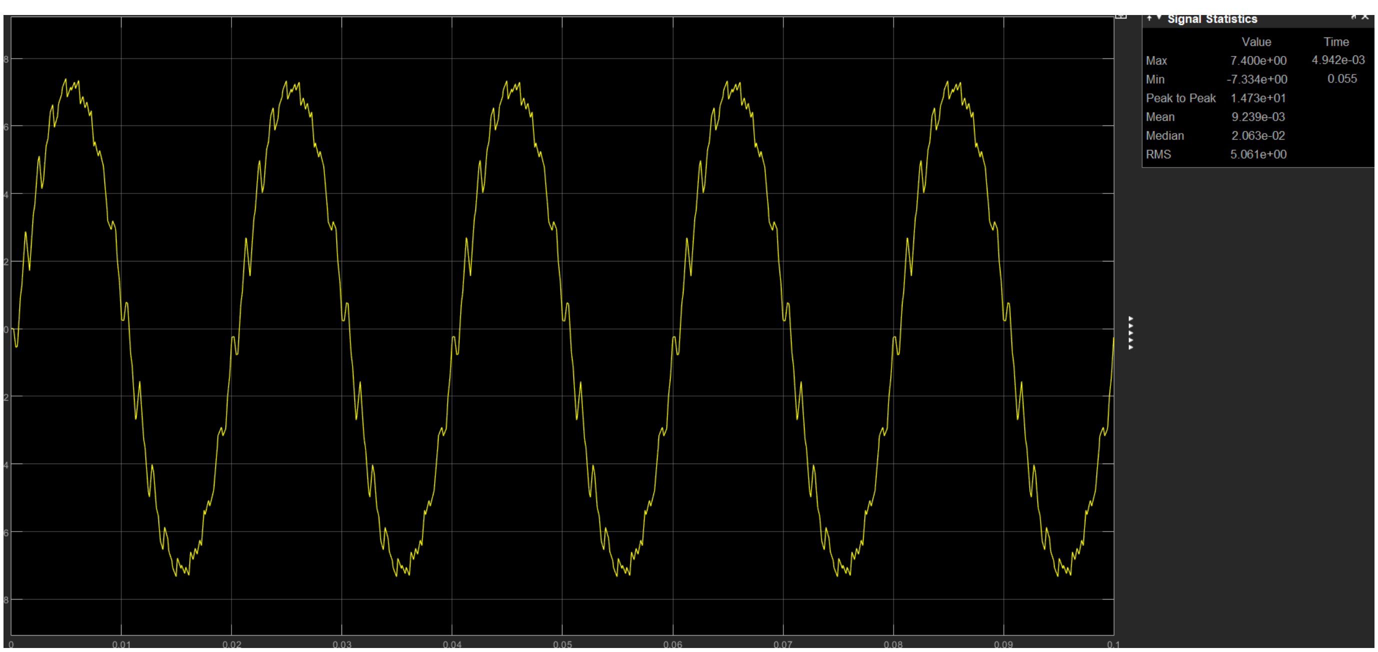


Fig. 5. Output current statistics using PWM inverter

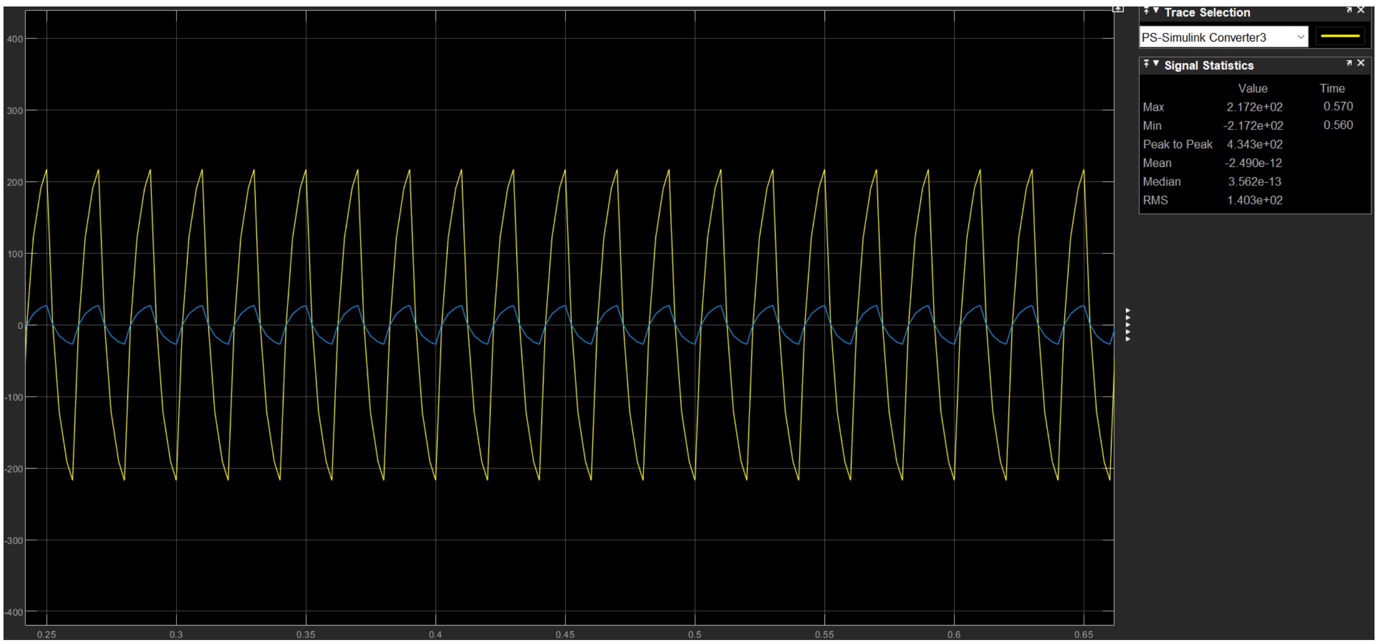


Fig. 6. Output voltage and current signals using square wave inverter

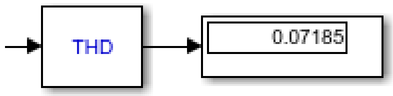


Fig. 7. THD value while using PWM inverter

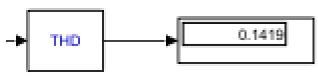
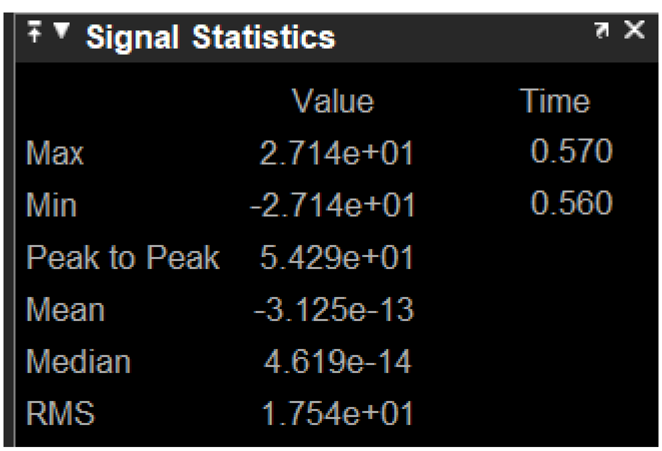
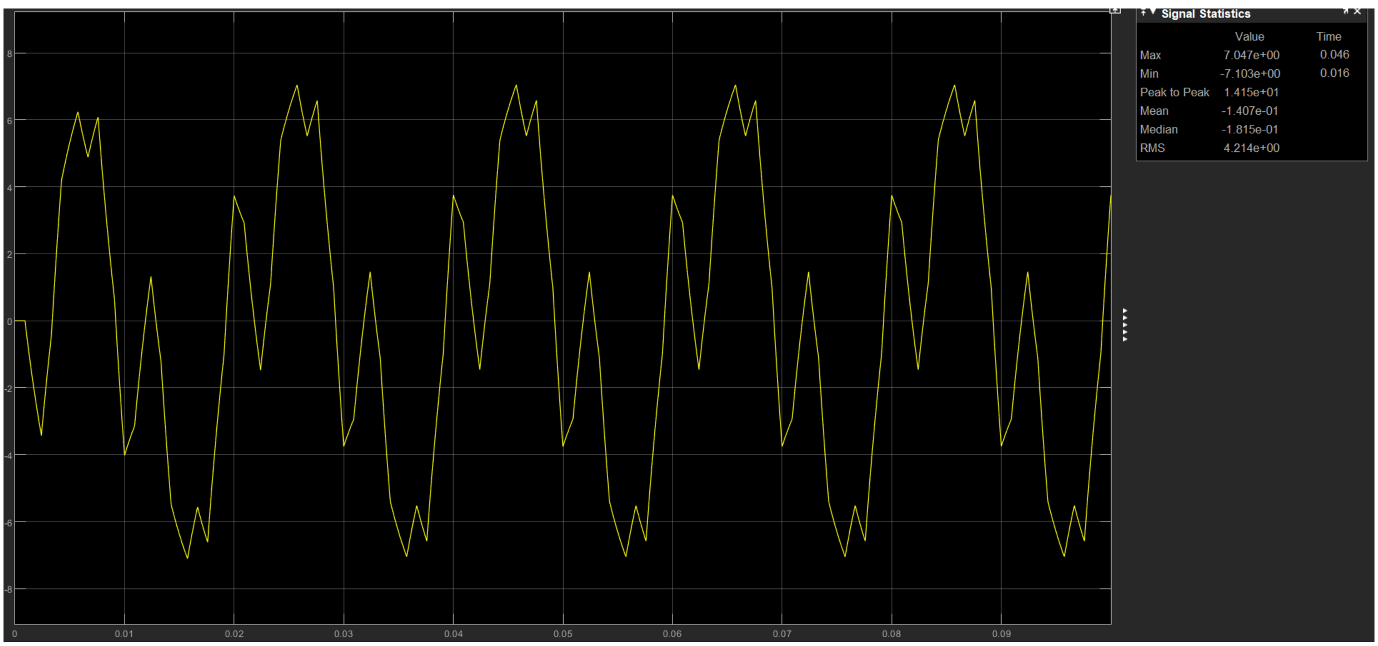


Fig. 8. THD value while using Square wave inverter


Signal Statistics

	Value	Time
Max	2.714e+01	0.570
Min	-2.714e+01	0.560
Peak to Peak	5.429e+01	
Mean	-3.125e-13	
Median	4.619e-14	
RMS	1.754e+01	

Fig. 9. Output current signal statistics using square wave inverter



Signal Statistics
Value
Time
Max
7.047e+00
0.046
Min
-7.103e+00
0.016
Peak to Peak
1.415e+01
Mean
-1.407e-01
Median
-1.815e-01
RMS
4.214e+00

Fig. 10. mf=3