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A 31 Level Multilevel Inverter Topology For A Grid Connected System Using Fuzzy Logic Controller

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ABSTRACT

This paper presents a novel 31-level multilevel inverter (MLI) topology for grid-connected renewable energy systems, integrated with a Fuzzy Logic Controller (FLC) to enhance system performance and power quality. The proposed inverter architecture significantly reduces the number of power switches and passive components compared to conventional topologies, achieving a high-resolution output with minimal complexity. By producing a near-sinusoidal voltage waveform, the 31-level inverter minimizes Total Harmonic Distortion (THD) and ensures compliance with IEEE-519 harmonic standards. To address the challenges of grid variability and nonlinear load dynamics, a Fuzzy Logic Controller is implemented to optimize the modulation index and switching signals in real-time. Unlike traditional PI controllers, the FLC offers robustness against parameter variations and improves dynamic response under transient and unbalanced conditions. The controller uses input variables such as error and change in error to generate control actions that enhance inverter output stability and grid synchronization. Extensive simulations conducted in MATLAB/Simulink validate the effectiveness of the proposed system. Results demonstrate superior voltage waveform quality, reduced THD (below 3%), fast dynamic response, and reliable operation under varying load and input conditions. The combination of a high-performance 31-level inverter and intelligent fuzzy-based control makes the proposed system highly suitable for modern grid-connected applications, including solar PV, wind energy systems, and smart grid interfaces

1.INTRODUCTION

1.1 Background

Microgrid technology is increasingly recognized for its ability to supply reliable power to remote and off-grid areas where conventional transmission infrastructure is not feasible. In addition to expanding energy access, microgrids contribute to improved energy efficiency through better management and reduced losses. Central to microgrid operation is the inverter, a power electronic device that converts direct current (DC) into alternating current (AC), which is required for most residential, commercial, and industrial loads. With the growing demand for high power applications, traditional two-level inverters are becoming insufficient, prompting a shift toward multilevel inverter (MLI) topologies. MLIs offer several advantages, such as improved output voltage quality, reduced total harmonic distortion (THD), and

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decreased need for bulky output filters. These features make them especially suitable for renewable energy systems including solar and wind, where power quality and conversion efficiency are critical. Transformer less photovoltaic inverters have gained popularity due to their lower cost, reduced weight, compact size, and minimal ground leakage current, making them an ideal choice for modern PV systems. A multilevel inverter can be constructed by cascading two conventional voltage source inverters (VSIs) using an open-winding transformer, which enables higher voltage levels and increased efficiency. However, realizing a 31-level inverter typically requires a large number of power switches and H-bridge circuits, leading to greater circuit complexity

1. **Number of Output Voltage Levels (N) for Multilevel Inverter**

For a cascaded H-bridge multilevel inverter:

$$N = 2^m + 1$$

where

m = number of inverter levels per phase or number of H-bridge cells.

Since you have a **31-level** inverter,

$$31 = 2^m + 1 \implies 2^m = 30 \implies m \approx 4.9$$

This suggests a specific topology or combination of bridges is used to get 31 levels (non-power-of-two structure).

2. **Total Harmonic Distortion (THD)**

THD of output voltage is:

$$\text{THD} = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100\%$$

where

V_1 = RMS voltage of the fundamental frequency component

V_h = RMS voltage of the h^{th} harmonic component

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2.LITERATURE SURVEY

1. Access to reliable electricity in rural and off-grid areas is a critical challenge, particularly for institutions like schools. Biru et al. (2020) propose standalone DC microgrids as an efficient and cost-effective solution tailored for rural schools. Their work emphasizes reduced conversion losses, seamless integration of solar PV and battery storage, and optimized system design to meet specific load demands.

2. Mothilal et al. (2018) focus on photovoltaic (PV) microgrids for rural electrification, highlighting the importance of system sizing, load forecasting, and control strategies such as MPPT and energy management systems to ensure reliable power supply. They also note the positive socio-economic impacts of deploying scalable and affordable PV microgrids in remote communities.
3. On the power electronics front, Hinago and Koizumi (2010) introduce a novel single-phase multilevel inverter design using switched series/parallel DC voltage sources. This inverter topology improves voltage level generation with fewer components, offering better efficiency, modularity, and fault tolerance. Such advancements are crucial for renewable energy applications in microgrids where compact and flexible inverter solutions are needed.

3.NON-CONVENTIONAL ENERGY SOURCES

3.1 Wind Energy System Overview

This project focuses on the design and control of a 31-level multilevel inverter for a grid-connected wind energy system. Wind turbines generate variable power due to changing wind speeds, which can affect power quality. To solve this, a high-level inverter is used to convert the irregular power from the wind turbine into a smooth, grid-compatible AC output.

Components of a Wind Energy System

Wind Turbine

Rotor blades: Capture wind energy and convert it into rotational mechanical energy.

Hub: Connects blades to the main shaft.

Nacelle: Houses the gearbox, generator, and control electronics.

Tower: Supports the turbine at a height where wind speed is optimal.

Gearbox

Increases the rotational speed from the slow-turning blades to the higher speed needed by the generator.

Generator

Converts mechanical energy into electrical energy. Types: Synchronous, Induction, Permanent Magnet Generators.

Control System

Monitors wind speed, direction, and turbine performance.

Controls blade pitch and yaw to optimize power capture and protect the turbine during high winds.

Power Electronics

Converts generated electricity to the required voltage and frequency. Includes inverters for grid connection.

Grid Connection System

Interface for feeding electricity into the power grid. Includes transformers, switchgear, and protection systems.

Working Principle

Wind flows over the blades creating lift and causing them to rotate. The rotor shaft spins the generator via the gearbox. The generator produces electrical energy.

Control systems adjust blade pitch and yaw to optimize efficiency and ensure safety. Power electronics condition the electricity before feeding it into the grid or local loads.

Types of Wind Turbines

Horizontal Axis Wind Turbine (HAWT): Most common; blades rotate around a horizontal axis.

Vertical Axis Wind Turbine (VAWT): Blades rotate around a vertical axis; less common, but useful in specific applications.

Advantages of Wind Energy Systems

1. Renewable and inexhaustible energy source.
2. No greenhouse gas emissions during operation.
3. Low operating costs once installed.
4. Can be installed onshore or offshore.

Challenges and Considerations

1. Intermittency: Wind is not constant, affecting power output.
2. Noise and aesthetic concerns.
3. Impact on wildlife (birds and bats).
4. Initial capital costs can be high.
5. Need for proper site assessment for optimal wind speeds.

Applications

1. Utility-scale wind farms feeding the grid.
2. Distributed generation for remote or off-grid locations.
3. Hybrid systems combined with solar or other renewable sources.

3.2 Solar Photovoltaics

The photovoltaic effect, which is how we turn sunlight into electricity, was first described by a scientist named Becquerel. When light hits two electrodes connected to a solid or liquid, it creates electric voltage. Solar cells are the devices that use this effect to convert sunlight into electricity. A single solar cell is called a photovoltaic cell, and when many of these cells work together, they form a solar module or solar array. These solar arrays can act like power plants, turning sunlight into electricity for homes, businesses, and factories. Smaller groups of solar cells are often called solar panels. Most solar panels are made from semiconductor materials, with silicon being the most common choice.

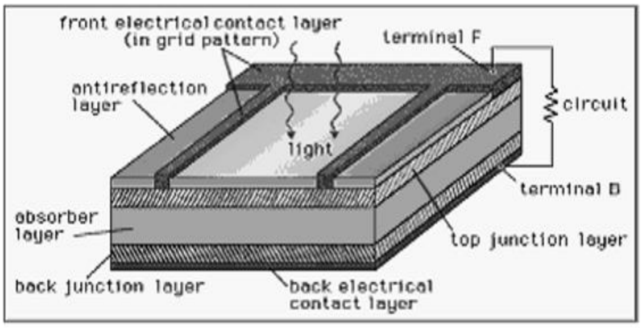


Fig 2.1 Solar Cell

The equivalent circuit for a solar cell is made up of a diode and a current source, where the photocurrent is directly related to how much sunlight is hitting the solar panel.

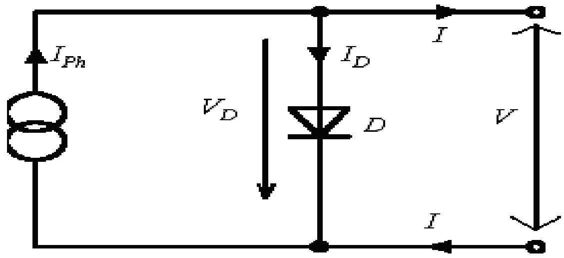


Fig 2.4 Equivalent circuit of a solar cell

The *V-I* equation of the simplified equivalent circuit could be derived from Kirchhoff's current law

$$I = I_{Ph} - I_D = I_{Ph} - I_S \cdot (\exp(\frac{V}{m \cdot V_T}) - 1) \quad \text{...(2.1)}$$

Where

I_{Ph} --- Photo current

I_D --- Diode current

I_S --- Diode reverse saturation current

m --- Diode ideal factor

V_T = (k*T)/q is Thermal voltage (25.7 mV at 25°C)

k = Boltzmann Constant=1.3824*e-23

T = AbsoluteTemperature

q = charge of an electron=1.60*e-19 couloumbs

V = output voltage of the solar cell

I = output current through the solar cells

The basic equivalent circuit model of a solar cell does not accurately represent the detailed electrical behavior within the device. In practical solar cells, voltage losses occur as the current travels toward the external terminals. These losses are typically modeled using a series resistance (Rs) which accounts for resistive effects within the cell and its contacts.

4.IMPLEMENTATION OF 31 LEVEL MULTILEVEL INVERTER

Putting in a 31-Level Solar-Powered Inverter with Fewer Switches. Figure 1 indicates the proposed 31-level inverter, which has ten unidirectional energy switches (Q1, Q2, Q3, Q4, Q5, Q6, Q7, Q8, Q9, Q10) and 4 terminal voltages from photo voltaic modules (ST1, ST2, ST3, ST4). According to this topology, the photo voltaic system's terminal voltages will be correctly short-circuited if the switching units (Q1, Q2), (Q3, Q4), (Q5, Q6), and (Q7, Q8) all characteristic simultaneously. Because of this, these switches need to no longer be capable to be grew to become on at the equal time. Also, Q9 and Q10 ought to no longer be became on at the identical time.

The proposed topology for a multilevel inverter is depicted in Figure 1. In the advised regularly occurring topology, the following formulation are utilized to decide the output voltage tiers (Nstep), the wide variety of switches (Nswitch), the wide variety of photo voltaic modules (Nsource), and the most voltage degree produced (Vo,max): The multilayer inverter can assist create wind and photo voltaic PV services on its very own. It works nicely with structures that use each wind and photo voltaic energy. Figure two shows a plan for an impartial microgrid that makes use of solar panels and wind mills to make electrical

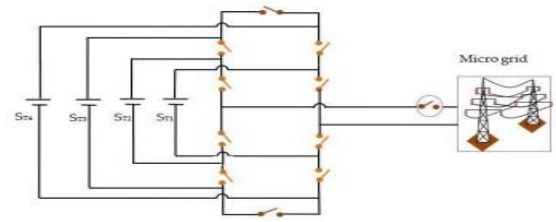


Fig 4.1 Proposed Multilevel Inverter Topology

The magnitudes of the solar terminal voltage sources of the proposed 31-level inverter are recommended as follows:

$$S_{T1} = S_{T,}$$
$$S_{T2} = 2S_{T,}$$
$$S_{T3} = 5S_{T,}$$
$$S_{T4} = 10S_{T,}$$

4.1 Switching Pattern of 31-Level Inverter

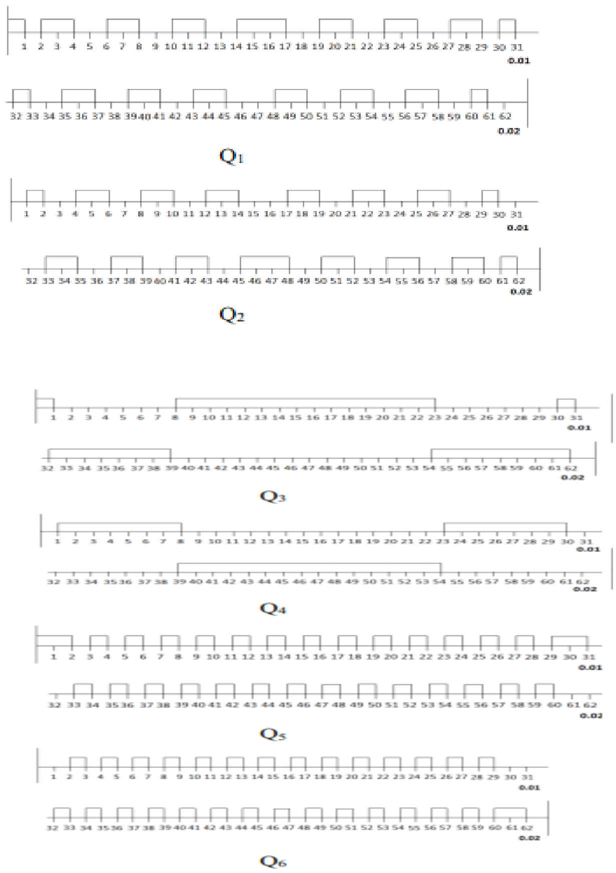
Table 4.1 illustrates the switching pattern used for the 31-level multilevel inverter. Calculating individual pulse generator values for IGBT triggering often leads to increased complexity. To simplify this, the design replaces conventional pulse generators with a repeating sequence block, into which the switching pattern is programmed.

SN	Voltage(v)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
1	0	1	0	1	0	1	0	1	0	1	0
2	S_{T3}	0	1	0	1	1	0	0	1	0	1
3	S_{T1}	1	0	0	1	0	1	0	1	0	1
4	$S_{T3} + S_{T1}$	1	0	0	1	1	0	0	1	0	1
5	$S_{T4} - S_{T3}$	0	1	0	1	0	1	1	0	0	1
6	S_{T4}	0	1	0	1	1	0	1	0	0	1
7	$S_{T4} + S_{T1} - S_{T3}$	1	0	0	1	0	1	1	0	0	1
8	$S_{T4} + S_{T1}$	1	0	0	0	1	0	1	0	0	1
9	$S_{T2} - S_{T1}$	0	1	1	0	0	1	0	1	0	1
10	$S_{T3} - S_{T1} + S_{T2}$	0	1	1	0	1	0	0	1	0	1
11	S_{T2}	1	0	1	0	0	1	0	1	0	1
12	$S_{T3} + S_{T2}$	1	0	1	0	1	0	0	1	0	1
13	$S_{T4} + S_{T2} - S_{T3} - S_{T1}$	0	1	1	0	0	1	1	0	0	1
14	$S_{T2} + S_{T4} - S_{T1}$	0	1	1	0	1	0	1	0	0	1
15	$S_{T4} + S_{T2} - S_{T3}$	1	0	1	0	0	1	1	0	0	1
16	$S_{T4} + S_{T2}$	1	0	1	0	1	0	1	0	0	1
17	$S_{T4} + S_{T2} - S_{T3}$	1	0	1	0	0	1	1	0	0	1
18	$S_{T2} + S_{T4} - S_{T1}$	0	1	1	0	1	0	1	0	0	1
19	$S_{T4} + S_{T2} - S_{T3} - S_{T1}$	0	1	1	0	0	1	1	0	0	1
20	$S_{T3} + S_{T2}$	1	0	1	0	1	0	0	1	0	1
2	S_{T2}	1	0	1	0	0	1	0	1	0	1

1											
22	S_{T3} $-S_{T1}$ $+S_{T2}$	0	1	1	0	1	0	0	1	0	1
23	S_{T2} - S_{T1}	0	1	1	0	0	1	0	1	0	1
24	S_{T4} + S_{T1}	1	0	0	1	1	0	1	0	0	1
25	S_{T4} + S_{T1} - S_{T3}	1	0	0	1	0	1	1	0	0	1
26	S_{T4}	0	1	0	1	1	0	1	0	0	1
27	S_{T4} - S_{T3}	0	1	0	1	0	1	1	0	0	1
28	S_{T3} + S_{T1}	1	0	0	1	1	0	0	1	0	1
29	S_{T1}	1	0	0	1	0	1	0	1	0	1
30	S_{T3}	0	1	0	1	1	0	0	1	0	1
31	0	1	0	1	0	1	0	1	0	1	0

Table 4.1 Switching pattern of 31 level Inverter

According to the switching pattern, the switching diagram of ten power devices has been drawn below and it is shown in Fig.4.2. The multilevel output of the inverter is shown in Fig.4.3



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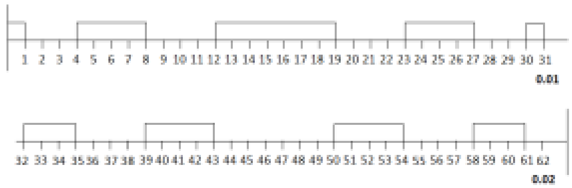
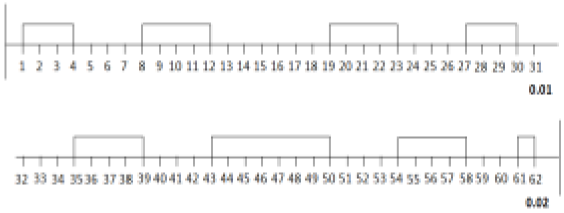
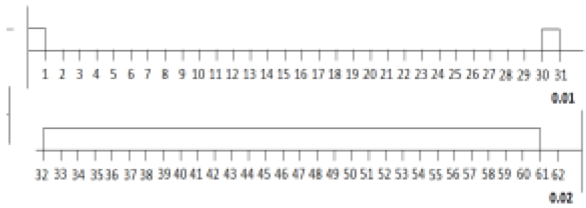


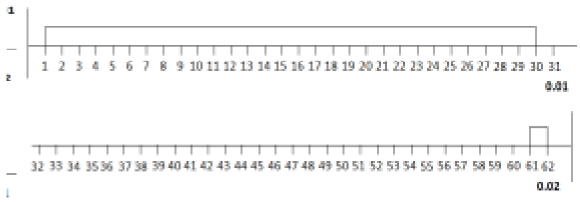
Q7



Q8



Q9



Q10

Fig 4.2 Switching signals to 10 switches Q1 to Q10 of the MLI.

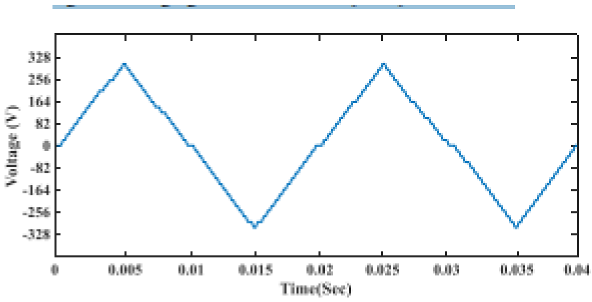


Fig 4.3 31 Level Multilevel Inverter Output

4.2 31 Level Multilevel Inverter using SPWM Technique

In this work, a Sinusoidal Pulse Width Modulation (SPWM) technique is employed to control the inverter switching operation. A closed-loop SPWM controller, as illustrated in Fig 4.4, dynamically regulates the voltage and frequency parameters to maintain the stability and performance of the microgrid.

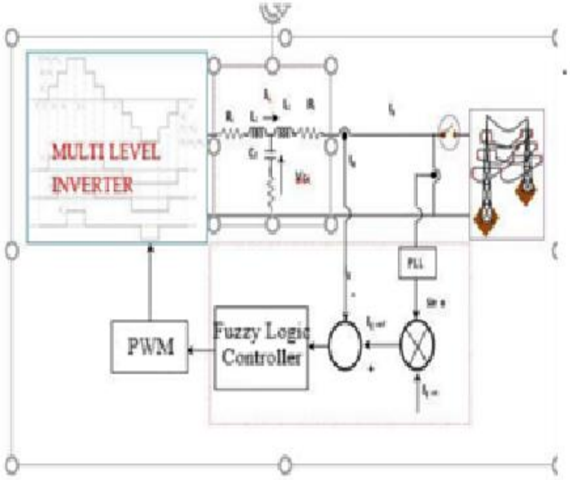


Fig 4.4 Multilevel Controller Diagram

A comparative analysis is presented in Table 2, highlighting key parameters of the multilevel inverter (MLI) for evaluation. These parameters include the number of switches (NSW), driver circuits (NDK), diodes (ND), capacitors (NC), sources (NSDC), component count per level (CC/L), and total standing voltage (TSV).

	Ref	N_{SW}	N_{DK}	N_D	N_C	N_{SDC}	N_{MCD}	CC/L	TSV_{PU}
Switched-Capacitor	[15]	18	18	-	4	2	8	1.35	5.66
	[16]	12	10	-	4	3	4	0.93	5.87
Cross-Switched	[17]	16	16	2	4	2	8	1.29	5.67
31-level Asymmetrical	[18]	14	14	-	-	4	7	1.03	2.4
proposed	-	10	10	-	-	4	5	0.93	2.1

Table 4.2 Comparison of Proposed 31 level system with MLI Topologies

Fuzzy Logic controller

A Fuzzy Logic Controller (FLC) typically operates with two inputs—error (e) and change in error (de)—and one output, which is the control signal. These variables are represented using linguistic terms: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). All input and output variables are normalized within the range of [-10, 10]. The corresponding fuzzy rules, as outlined in Table IV, are formulated based on basic principles and expert knowledge of the system. Given that each input has seven fuzzy sets, the rule base can include up to 49 control rules, establishing relationships between inputs and outputs to define the control behavior.

CE \ E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

Table 4.3 Table of Fuzzy Logic

5.RESULTS AND DISCUSSION

A multilevel inverter is a power electronic device used to synthesize a desired AC voltage from multiple DC voltage sources. Instead of switching between just two levels (like in a traditional two-level inverter), multilevel inverters can produce multiple voltage levels at the output.

Output Voltage Levels:

- The output voltage of a multilevel inverter has multiple discrete steps, which approximate a sinusoidal waveform more closely.
- For an *n*-level inverter, the output voltage can take on (n) different voltage levels.

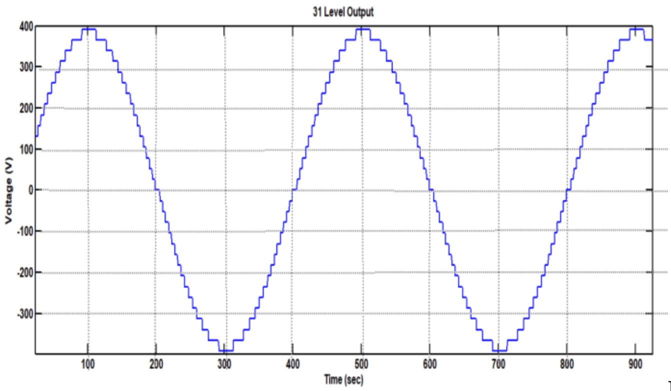


Fig 5.3 31 Level Multilevel Inverter Output

An inverter is a device that converts DC (Direct Current) into AC (Alternating Current). The inverter output is the AC voltage or current waveform produced at its terminals.

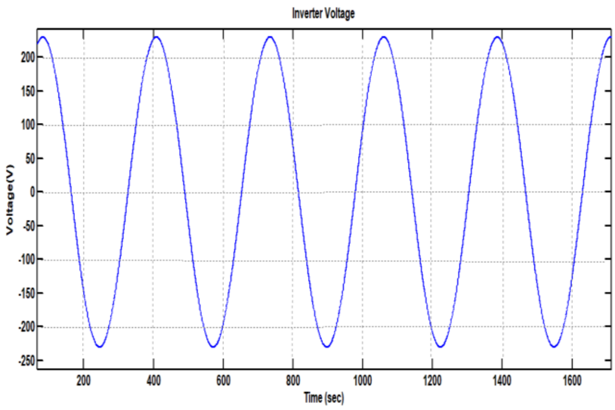


Fig 5.4 Inverter Output

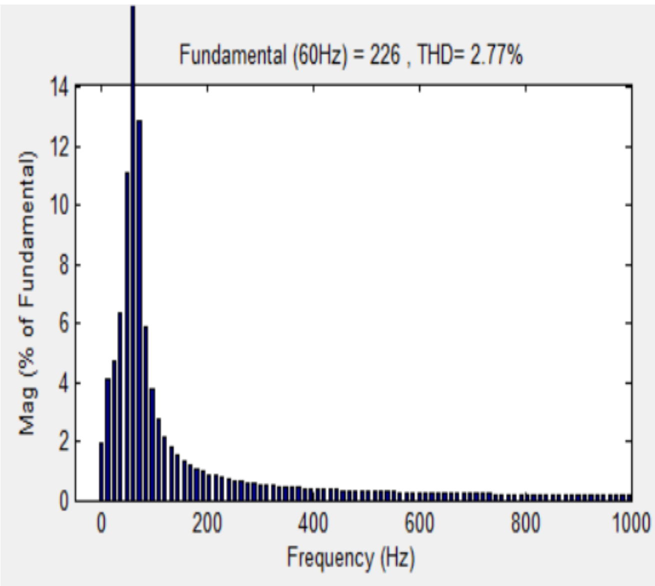


Fig 5.5 FFT Analysis Using Fuzzy

- **FFT (Fast Fourier Transform)** is a mathematical algorithm that converts a signal from the time domain into the frequency domain.
- It helps analyze the frequency components present in signals like inverter output voltages or currents.
- For example, it identifies harmonics, noise, and distortions.

CONCLUSION

This project presents a 31-level multilevel inverter topology integrated with a fuzzy logic controller for grid-connected renewable energy systems. The proposed system effectively reduces Total Harmonic Distortion (THD), delivering a high-quality, near-sinusoidal AC output suitable for grid integration. By employing fuzzy logic control, the system adapts intelligently to dynamic input variations and nonlinear behavior, ensuring stable and efficient performance without relying on complex mathematical models. The multilevel inverter structure not only enhances waveform quality but also reduces switching losses, electromagnetic interference, and stress on power devices. Simulation results confirm that the combination of advanced inverter design and intelligent control achieves reliable operation, improved power quality, and grid compliance. This work contributes to the development of scalable and efficient power conversion systems for renewable energy applications.

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