Journal of Engineering Sciences
Vol 13, Issue 06, June/2022
ISSN NO:0377-9254

Output Voltage Regulation Techniques Improve Power Quality in Solar-Fed Cascaded Multilevel Inverters

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Abstract *Providing rural areas with access to electrical electricity is a critical prerequisite for increasing sustainable living conditions, and it is at the top of many developing countries' agendas. However, there are other obstacles in the solar energy system, such as a mismatch between PV generated power and demand, which leads to a slew of additional issues. When harmonics are present in a solar photovoltaic (PV) energy conversion system, the power quality degrades. To solve this issue, the goal of this study is to examine the use of a Fuzzy Logic Controller to eliminate harmonics in a solar-fed cascaded multilevel inverter (FLC). Unlike other techniques such as Proportional Integral (PI) and Artificial Neural Network (ANN), the proposed FLC-based approach aids in reducing harmonic distortions and providing output voltage regulation in terms of maintaining voltage and frequency at the inverter output end, resulting in improved power quality. Simulations for a solar-fed cascaded Multilevel inverter including a Fuzzy Logic Controller (FLC) will be run in MATLAB / Simulink and compared to Artificial Neural Networks (ANN).*

1. INTRODUCTION

The key component of power generating is to provide the lowest cost and highest quality of electricity to the loads. The most essential study subjects in society are energy efficiency, electrical supply, and sustainability. Sustainable, renewable, cost-effective, dependable, and secure energy is a vital prerequisite for a country's economic, human, and industrial development. Environmental concerns, depleting petroleum reserves, and a growing reliance on fossil resources from unstable regions have increased the importance of more efficient energy usage. Thermal and nuclear power plants, which have been used to generate energy for a long time, each have their own set of advantages and disadvantages. The growing awareness of the need to reduce carbon emissions (CO2) has fueled interest in non-fossil fuel research as a source of energy. As a result, all sectors, including residential, transportation, manufacturing, and agricultural, demand a more sustainable energy source. The energy suppliers have been motivated to grow further and alter the energy system in a more effective manner as a result of this unforeseen strain and threat to the environment. In recent years, the complexity of various energy legislation has been decreased, while investment opportunities in the energy industry have risen throughout the world.

Renewable energy may be defined as life derived from an infinite supply of natural resources. Sunlight, water, air, biomass, and geothermal heat are just a few examples of natural renewable energy resources. In contrast to other kinds of energy, such as fossil fuels, which are confined and concentrated to certain places, the scope and prospects for renewable energy resources are extensive throughout a given geographical region. The economic, efficiency, and energy security benefits of fast deployment of renewable energy are enormous, and they would result in considerable energy security while minimizing environmental consequences. This includes good changes such as enhanced healthcare and lower infant mortality rates as a result of reduced pollution, as well as governments saving millions on healthcare. In rural locations, renewable energy frequently replaces conventional energy in the generation of electricity, water heating, transportation, and energy services (off grid). In this regard, renewable energy assets are likely to serve as a catalyst for expanding and improving energy access in rural regions. PV technologies, solar heating, concentrated solar power, and concentrated photovoltaics are all ways to collect solar energy from the sun, and they're all classified by how the energy is caught, transformed, and delivered.

They are divided into two categories: active and passive. Using the photoelectric effect, a PV system turns light into electrical energy. The photovoltaic system consists of a series of silicon semiconductors that collect photons and convert them to electrons. Converters are used to convert the generated DC to AC. As a result, using a specialized MPPT system to maximize the energy absorbed from the sun is critical. Sun-tracking PVs are commonly used to do this. Sun-tracking PVs do this by adapting to global solar isolation variations and amplifying the captured sunlight radiation to create maximum power at a constant voltage. The capacity to convert sunshine into energy is used to determine the efficiency of a solar array, and it is an extremely important component to consider when selecting the proper panel for a PV system. Solar PVs can be effectively incorporated into the mainstream power supply as a dependable RE source. However, there are other obstacles in the solar energy system, such as a mismatch between PV generated power and demand. This is due mostly to PV's erratic production. It leads to a slew of additional issues, one of which being voltage control. The employment of active and reactive powers has controlled voltage in transmission and distribution over the years. The difference in voltage between two endpoints, i.e. transmission and distribution, is referred to as voltage regulation. STATCOMs and SVCs are two devices that work together to guarantee that the voltage across the load is kept within allowable limits. The existence of impedance causes voltage control issues, resulting in either overvoltage or voltage decreases below normal under severe load situations. Solar energy, in particular, has grown in popularity. Over the last 20 years, demand for solar-electric energy has steadily increased by 20%–25% every year.

A power electronic interface between the source and load is recommended to alleviate the voltage imbalance, with the purpose of providing output voltage management while also increasing power quality. The proposed work is unique in that it employs a multilayer inverter to provide a twofold

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benefit. The three level converters gave rise to the name "multilevel." The semiconductor switches' commutation combines numerous DC sources to attain high output voltage levels. Multilevel inverters provide several advantages, including higher power quality, greater electromagnetic compatibility, decreased switch losses, and increased voltage capabilities. Neutral Point Clamped or Diode Clamped Multi Level Inverter, Flying Capacitor Multilevel Inverter, and Cascaded Multilevel Inverter are the three architectures of MLI. The Cascaded Multilevel Inverter (CMLI) is used in this research. CMLI's principal function is to synthesis a desired voltage from separate DC sources (SDCs), such as batteries or solar cells. Asymmetrical inverters are highly suggested since solar PV voltages are changeable due to environmental conditions. DC link voltages in asymmetrical inverters are different. CMLI uses the fewest components compared to other multilevel inverters to accomplish the same amount of voltage levels. The CMLI's sole drawback is that it requires separate DC sources for genuine power conversions. This disadvantage, however, can be mitigated by using solar PV as an input. In light of this, the study explains how to reduce the complexity of voltage regulator management and increase power quality in a solar power circuit.

2. MULTILEVEL INVERTER AND PWM

With the use of suitable transformers, switching, and control circuits, an inverter transforms direct current (DC) to alternating current (AC). The converted AC can be at any desired voltage and frequency.

Static inverters are utilized in a broad range of applications, from small switching power supply in computers to big electric utility high-voltage direct current applications that transmit bulk power, and they have no moving components. Inverters are widely used to convert DC electricity from solar panels or batteries into AC power.

A high-power electronic oscillator is used in the electrical inverter. It got its name because early mechanical AC to DC converters were designed to function backwards, or "inverted," in order to convert DC to AC. A rectifier's opposite function is performed by an inverter.

Cascaded h-bridges inverter

Figure 1 shows the single-phase construction of an m-level cascaded inverter. A single-phase full-bridge, or H-bridge, inverter is linked to each distinct dc source (SDCS). By connecting the dc source to the ac output using different combinations of the four switches, S1, S2, S3, and S4, each inverter level may provide three distinct voltage outputs, +Vdc, 0, and –Vdc. Switches S1 and S4 are switched on to gain +Vdc, while switches S2 and S3 are turned on to obtain –Vdc. The output voltage is 0 when S1 and S2 or S3 and S4 are turned on. The ac outputs of the various full-bridge inverter levels are linked in series, resulting in a synthetic voltage waveform that is the sum of the inverter outputs. The number of output phase voltage levels m in a cascade inverter is defined by m = 2s+1, where s is the number of separate dc sources. An example phase voltage waveform for an 11-level cascaded H-bridge inverter with 5 SDCSs and 5 full bridges is shown in

Figure. The phase voltage $v_{an} = v_{a1} + v_{a2} + v_{a3} + v_{a4} + v_{a5}$.

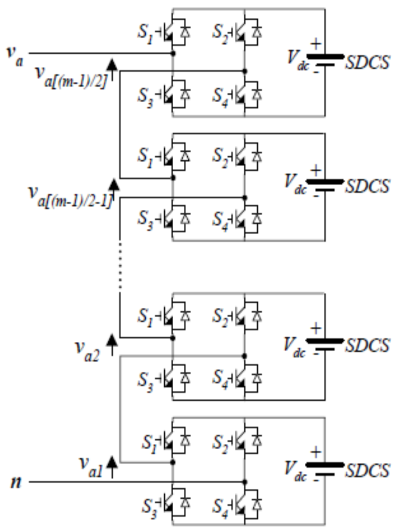

Fig 1: Single-phase structure of a multilevel cascaded H-bridges inverter

The magnitudes of the Fourier coefficients when normalized with respect to V_{dc} are as follows:

$$H(n) = \frac{4}{\pi n}\left[\cos(n\theta_1) + \cos(n\theta_2) + \ldots + \cos(n\theta_s)\right], \quad \text{where } n = 1, 3, 5, 7, \ldots$$

The conducting angles, 1, 2,... s, can be selected to minimize voltage total harmonic distortion. In general, these angles are set to eliminate the 5th, 7th, 11th, and 13th harmonics, which are the most common lower frequency harmonics. In the following part, we'll go through harmonic removal approaches in greater depth.

For applications such as static var generation, an interface with renewable energy sources, and battery-based applications, multilevel cascaded inverters have been suggested. Three-phase cascaded inverters can be coupled in a wye, as shown in Figure 2.

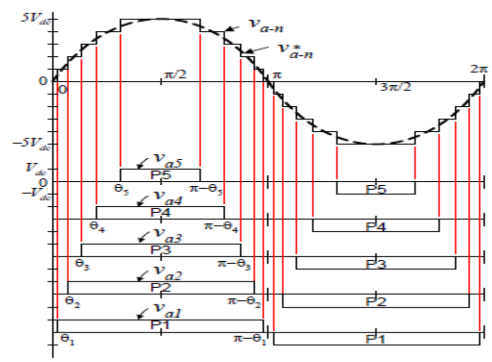

Fig 2: Output phase voltage waveform of an 11-level cascade inverter with 5 separate dc sources

Pulse widths modulation

By switching the solar system controller's power devices, pulse width modulation (PWM) is the most effective way to achieve constant voltage battery charging. Consider a waveform like this: it is a voltage alternating between 0v and 12v while in PWM regulation, the current from the solar array tapers according to the battery's condition and recharging demands. Because the voltage is at 12 volts for precisely the same amount of time as it is at 0 volts, a suitable device attached to its output will perceive the average value and believe it is being fed 6 volts - exactly half of 12 volts. We may change the 'average' voltage by altering the width of the positive pulse.

3. EXISTING SYSTEM

This technique shows how to manage the electricity generated in photovoltaic (PV)

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ISSN NO:0377-9254

modules using an adaptive strategy based on multiple topologies of artificial neural networks (ANNs). Adaptive systems and artificial neural networks (ANNs) are nonlinear elaboration information systems whose behavior is inspired by the biological nervous system. It is difficult to build a mathematical model for a system where there is no apparent link between the inputs and outputs; on the other hand, the ANN can represent this system using samples. ANNs are more versatile and powerful than other parametric techniques because of their capacity to learn from experimental data. As a result, neural networks have become quite popular in many domains for tackling regression and classification issues. The neural network functions as a black box since it does not require any particular knowledge about the system or process.

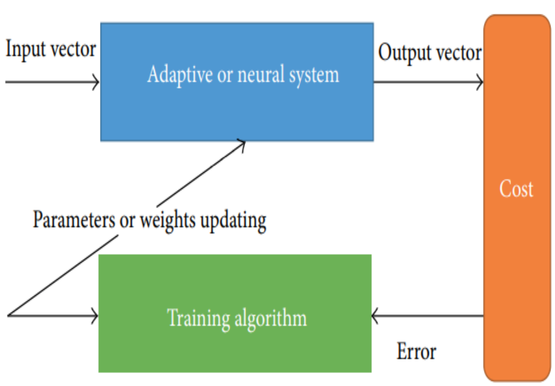

Fig 3: Adaptive or neural system's design

The Artificial Neuron:

An artificial neural network (ANN) is made up of numerous interconnected processing nodes known as neurons, which operate as microprocessors. Each artificial neuron (Figure 4) takes a set of weighted inputs and generates an output. The activation potential Ai of an ANN is equal to

$$Ai = N \sum j{=}1\; wijxj - bj,$$

The bias is a coefficient that governs the activation of the signal handled by the ANN, where N is the number of elements in the input vector xi, ij are the interconnection weights, and bi is the "bias" for the neuron. Only information that is locally available at the neuron, either stored internally or received via the weighted coefficients, determines the neuron output.

The Activation Function

The neuron output yi is calculated by the summation of weighted inputs with a bias through an "activate on function" as follows:
$yi = \Phi\ (Ai) = \Phi\ [\ N \sum i{=}1\ \omega ijxi - bi]$.
The activation function is intended to limit the output of the neuron, usually between the values [0, 1] or [–1, +1]. Typically, it is used the same activation function for all neurons in the network, even if it is not necessary [21]. The most commons activate functions are the step function, the linear combination, and the sigmoid function as shown in Figure 3.3. In the step function, the output $\Phi(Ai)$ of this transfer function is binary, depending on whether the input meetsa specified threshold. The "signal" is sent that is, the output is set to one, if the activation meets the threshold:
$yi = \Phi\ (Ai) = \{1$ if $A \geq$ threshold 0 if $A <$ threshold$\}$.

The step activation function is particularly effective in the last layer of an ANN for doing binary input categorization. The weighted sum input of the neuron plus a linearly dependent bias forms the system output in a linear combination, which is generally more beneficial in the initial layers of an ANN. A number of such linear neurons perform a linear transformation of the input vector as,

$yi = \Phi\ (Ai) = kAi$, in which k is a scale parameter.

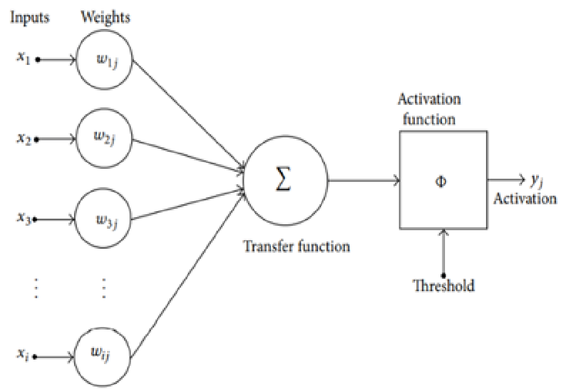

Fig 4: Schema of artificial neuron

Artificial neural network based controller

Rather of having a clear separation of sub tasks to which individual units are allocated, neural networks collectively perform functions and by the units in parallel. The neural networks-based controller offers the appropriate voltage regulation for the input-output dataset. Verror = Vref – Vactual is the formula for calculating voltage error values. The ANN is trained using these error values. The ANN can offer the ideal switching angles for the inverter circuit to maintain the constant voltage at its output end for the suitable levels of error signals. The training procedure of ANN consists of the following steps: 1) Provide the input output data set, 2) Calculate the weights and 3) Update the weights based on the input changes. The neural network is trained for various samples at different intervals to process the error signal.

4. PROPOSED SYSTEM

Many strategies may be used to improve the power quality of inverters. One method is to increase power conversion by cascading inverters, which reduces switching losses and improves power quality. By cascading the inverters, the resultant inverter power is transformed into high voltage at a lower frequency and low voltage at a higher frequency. With a single DC supply, two three phase three level inverters with a voltage THD of 9% were shown. Because of the popularity of multilayer power converters, several researchers have worked to enhance them. There has been some noteworthy study done. As a result of renewable energy systems, distributed generation systems have emerged, with many houses adopting solar power, micro-CHP and other technologies to provide electricity. As a result, utility networks have had to establish higher requirements to assure power quality and islanding protection, as well as adapt to modern management systems for harmonic reduction. In this context, innovative ways for improving power quality while merging wind and solar generators, as well as storage technologies, were investigated. A novel technology called Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) was tested on a 3kVA prototype with a 96 percent efficiency in order to further decrease harmonic components in multilayer cascaded voltage source converters. The use

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ISSN NO:0377-9254

of several switches in a novel architecture for bidirectional power systems has increased the cost of deployment. Due to the various switching components, the related cost of the converters is often significant when cascading them.

The decrease in components will not only lower the components, but it will also aid in the reduction of losses. As a result, a series-connected sub-multilevel converter blocks were developed, with the goal of reducing not only the number of components, but also the installation surface area, switches, losses and converter cost. Reviewing the different systems, the technology was leveraged to demonstrate a 96 percent efficient stand-alone renewable energy system. Abu-Rub et al. used the approach to decrease harmonic distortion in medium voltage systems by raising the power rating while decreasing switching frequencies and operating at low switching frequencies. The main goal of a multilevel converter is to synthesize inputs from several DC sources in order to provide a correct output voltage with minimal harmonics and other disruptions. On a single-phase multilevel inverter, the experiment was conducted utilizing several methodologies for calculating appropriate switching angles in order to create output voltage with lower THD and eliminate needed harmonic components. A thorough investigation was conducted utilizing a Fuzzy Logic (FL) based controller. With the H-bridge power sharing method, the FL-based controller was used.

Fuzzy Logic:

Fuzzy logic is all about the relative importance of precision. How important is it to be exactly right when a rough answer will do? We can use Fuzzy Logic Toolbox software with MATLAB technical computing software as a tool for solving problems with fuzzy logic. Fuzzy logic is a fascinating area of research because it does a good job of trading off between significance and precision—something that humans have been managing for a very long time. In this sense, fuzzy logic is both old and new because, although the modern and methodical science of fuzzy logic is still young, the concept of fuzzy logic relies on age-old skills of human reasoning.

The signal processing is carried out using mixed-mode programmable gate array. As a result, improved performance over the two-level inverters at low and medium power is obtained. The medium or high-power inverters often use optimal pulse width modulators as a contrivance for reducing the switching frequency leading to minimize the selective harmonic orders. Most of the selective harmonic algorithms are complex and based on linear equations resulting in inconsistencies. Proposed model is based on criteria based on four equation methods for multi and two-level inverters. A study on weight-oriented junction method for low level voltages is also undertaken and tested a new modulation technique based on P-Q theory for three phase transformers less inverters for eliminating leakage currents in the PV systems employing multilayer cascading inverter configuration. Here three, two and single vectors are applied to increase system utilization and concluded that the system can provide greater MPPT and compensation for current harmonics and reactive power.

Most of the multilevel series converters are based on PWM methods. This method IS based on multilevel parallel converters using interleaving techniques. The results indicate that the phase disposition shows high levels of load current ripples and influences the current balancing in the same phase. Further modified the design in Current Source Inverter (CSI) to achieve high reliability than the Voltage Source Inverter (VSI). The leakage current was suppressed without using the isolation transformer which increased the efficiency and thereby reducing the cost than the conventional. elucidated the single-phase grid connected CMLI by applying a balanced control strategy. It is based on energy sample data model and applied on a phase and level shifted PWM to ensure PV arrays are operating at optimum MPPT. a novel cascaded MLI using H-bridges was presented which involves reduced number of input DC sources and power switches with lesser blocking voltages. The mentioned features reduced the complexity and cost incurred for developing the inverter. In an effort to reduce the harmonics in a multilevel single phase transformer less grid connected system reference [20] proposed a new model of synthesizing up to 9 voltage levels for improving the common mode leakage current and regulating voltage in the flying capacitor. The doubling of the output voltage level can improve the power quality in the inverter systems. This strategy was tested by proposing a double level network (LDN) based multilevel inverter for reduction in inverter switching frequency. The topology uses a symmetrical H-bridge cascading while offering performance as equal to the asymmetrical system. The usage of three arm H-bridges greatly perk up the power quality while simultaneously decreasing the switching frequency, cost and size of the power filter.

5. ANALYSIS AND RESULTS

Multilevel converters include many DC lines to allow for separate control of possible voltage and MPP tracking at each string. An open-loop system is a solar-fed 15-level inverter with no voltage regulation (VR). Panels with varying levels of irradiance are created and linked to the various phases of the CMLI. Seven cascaded H bridges are joined in sequence for the fifteen floors. A reference and carrier signal are compared for pulse production. In order to generate a pulse signal, the reference sinusoidal and triangular carriers are compared.

The bipolar PDPWM method is used to generate the pulses. For pulse sequence, triangle wave and positive sinusoidal signal are compared for one leg, and triangular wave and negative sinusoidal signal for the other leg. Figure 6 depicts the change in an inverter output voltage as a PV panel is modeled with different irradiance levels. Figure 10 shows the output voltage waveform derived from solar PV modules with varying irradiance and partially shadowed situations.

This causes the uneven distribution of output voltage which results in a voltage imbalance situation. By adopting VR techniques, these uneven changes can be compensated

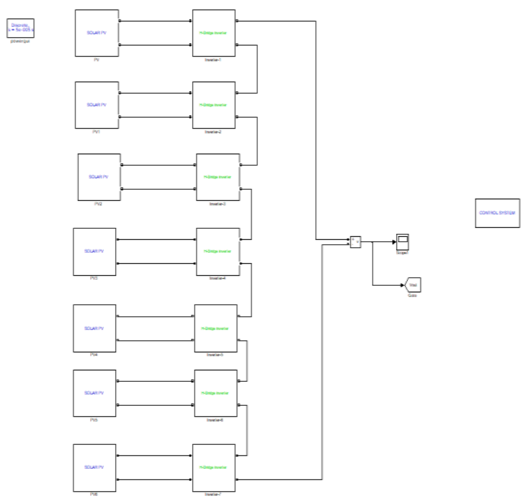

Fig 5: ANN Controller model

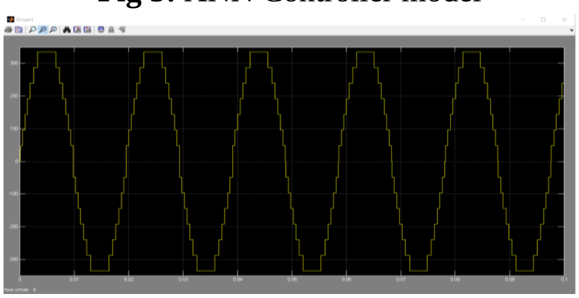

Fig 6: Simulated output response

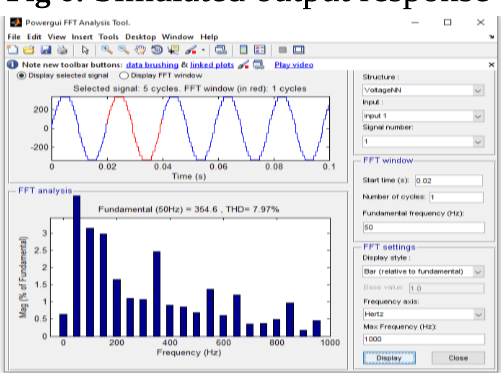

Fig 7: FFT Window representing Total Harmonic Distortion

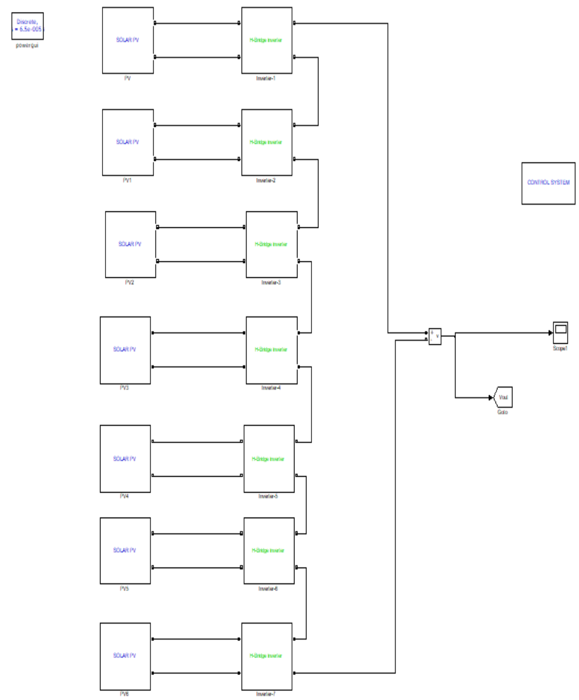

Fig 8: Fuzzy logic controller model

Fig 9: Fuzzy rule base design

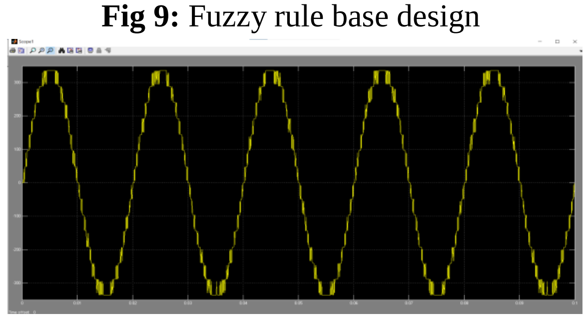

Fig 10: Simulated output response

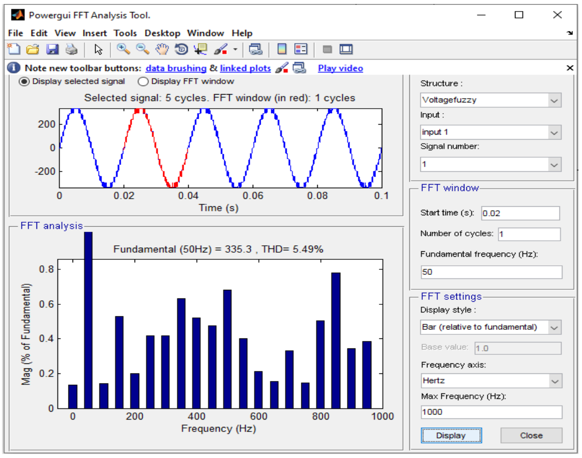

Fig 11: FFT Window representing Total Harmonic Distortion

6. CONCLUSIONS

For a solar-fed 15-level inverter, the voltage control structure, as well as power quality enhancement, is explored and executed both in simulation and in an experimental configuration. When the findings are considered, it is discovered that FLC produces superior VR outcomes when considering fluctuations in the input solar PV. Despite this, FLC is being investigated for the nine-level, however it will be implemented using DC power sources rather than solar panels.

All of the other approaches are used for low power and lower MLI topology levels. The commercial use of MLI by delivering a constant output voltage is explored, and the experimental findings show that the suggested system is effective. The technology can be used by consumers that demand grid engagement as well as improved power quality.

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