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Enhancing Power Quality in Solar-Fed Cascaded Multilevel Inverters: A Comparative Study of Fuzzy Logic and Neural Network Controllers for Output Voltage Regulation

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Abstract: Solar PV is one of the major sources of renewable energy generation. The global shift towards renewable energy sources necessitates a focus on improving power quality in solar based power generation. Multilevel Inverters are used to feed an AC load, harmonics gets added due to addition of these inverters which can lower the power quality. H-bridge power sharing method is proposed to optimize power quality in the inverters. The proposed system involves connecting each PV panel to an individual dc/ac inverter, which are then interconnected in series to achieve a higher voltage level. This configuration offers several advantages, including improved utilization of PV modules, the ability to integrate diverse sources, and the maintenance of system redundancy through the cascaded inverter setup. Furthermore, this cascaded inverter design eliminates the need for a central dc/ac inverter and per-string dc bus, resulting in increased overall efficiency. The independent voltage control facilitated by the separate dc connections enables unique maximum power point tracking (MPPT) control for each PV module, thereby maximizing the energy harvested from the solar panels. The study investigates the advantages of renewable energy by analyzing the performance of these controllers in terms of voltage stability and harmonic distortion. This research paper presents a comparative study of fuzzy logic and neural network controllers for output voltage regulation, aiming to enhance power quality in these cascaded multilevel inverters.

Keywords: *Solar-fed Cascaded Multilevel Inverters, H-Bridge Multilevel Inverters, Fuzzy Logic Controller, Neural Network Controller, Power Quality, Renewable Energy*

1. Introduction:

The growing awareness of the need to reduce carbon emissions (CO2) has fueled interest in non-fossil fuel research as a source of energy.[5] As a result, all sectors, including residential, transportation, manufacturing, and agricultural, demand a more sustainable energy source. Sustainable, renewable, cost-effective, dependable, and secure energy is a vital prerequisite for a country's economic, human, and industrial development. Solar energy is characterized by its inherent variability due to factors such as the position of the sun, time of day, atmospheric conditions, season, and the characteristics of the solar plant. [1] 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. Solar based PV systems play a vital role in increasing the utilization of renewable energy sources.

A PV system has PV modules which are connected to an MPPT scheme to identify changes in irradiance and select a maximum power operational point using the shortest path. A boost converter which uses a pulse width modulation (PWM) scheme, acts as a DC link voltage and connected to a voltage source inverter (VSI) which supplies the load. [9]

In order to extract maximum available energy from sun (since the intensity of solar irradiance, temperature and cloud cover keeps on changing continuously) MPPT (Maximum Power Point Tracking) Controller is needed. [7] Choosing a proper MPPT depends on functionality, applications, pros and cons of algorithms.[7] MPPT algorithms are of many types, the traditional P&O approach involves measuring the output voltage and current simultaneously then computing the power at each time the voltage and current are detected [19]. Reduction of computational time, oscillations and improved tracking efficiency is one of the major concerns when selecting and MPPT algorithm [19]

There is growing interest in grid-connected PV setups [2][17] due to the phenomenal market development of grid-connected photovoltaic (PV) systems but harmonics present in the system causes mismatch between generated power and received end power at grid side, thereby reducing the power quality. Solar PV systems needs to be integrated to a grid, but a flexible system with decreased line loss and generation cost and better compliance needs a better control scheme, this can also

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reduce the power loss and settling time. [18] Grid synchronization and monitoring is also an area of concern. [2][17]

Some literatures were gone through to identify some of the existing approaches to improve power output and quality of a solar PV system, some noteworthy points are mentioned below:

- Irradiance fluctuation between PV modules might cause the MPPT algorithms to operate inefficiently and result in an inaccurate control. [8] The PV system can be made more efficient by combining it with ANN and bio inspired forecasting methods to deal with upcoming uncertainties and in turn making better decisions which will help in improving power production. [5]
- Fuzzy Logic Controllers can be combined with MPPT and can determine the duty cycle based on the rule base, this improves output power and reduces settling time. [10]
- Biological inspired algorithms based on swarm optimization like Particle Swarm Optimization (PSO) and based on genetics like Genetic Algorithm (GA) can be used to optimize controllers, it helps in boosting the output power of a PV system with increased speed and accuracy. [11]
- Fuzzy Logic controllers combined with Pulse width Modulation techniques can also help in lowering source current and terminal voltage harmonics. [12]
- Selective harmonic elimination is a traditional approach but when combined with ANN can help in reducing no. of switching devices and in turn reduce switching frequency which shows lowered switching losses. [13]
- ANN based approach can also be used to remove lower order harmonics and reduce THD values by coupling it with multilevel inverters, where switching angles can be found out using suitable iterative techniques. [14]
- ANN based approach are used to make systems faster, accurate, effective [6] when deciding duty cycle of a converter connected to PV module, to make the system more reliable for off grid applications it can be connected to a lead acid battery and charge controllers.[15]

There are many techniques to improve power quality, one of which is by cascading the inverters which is called Multi Level Inverter (MLI) [3,4]. MLI combines the inputs from various DC sources and combine them to produce higher output voltage with minimum harmonic distortion. There is a relationship between the smoothness of a waveform and the voltage levels. As the voltage level increases, the waveform tends to become smoother. This is because higher voltage levels allow for a more continuous and less distorted representation of the waveform. [3] Multilevel inverters do have certain drawbacks that should be considered such as requirement of numerous electronic components, electromagnetic interference, bulkiness, driver circuit complexity, long reverse recovery periods, and Voltage balance concerns. [4][17]

The goal of this study is to examine the use of a Fuzzy Logic Controller (FLC) and Artificial Neural Network (ANN) based controller to eliminate harmonics in order to improve quality of power as well as to increase the overall efficiency of a cascaded Multi Level inverter (MLI) based PV system.

2. Methodology:

Solar energy has attracted significant attention as an eco-friendly and sustainable means of generating electrical power. The utilization of cascaded multilevel inverters has seen a growing popularity in the conversion of solar energy into usable electricity, primarily due to their capability to produce high-quality voltage waveforms and counteract harmonic disturbances. Nevertheless, achieving an optimal power quality level remains a persistent challenge, particularly in the face of fluctuating solar irradiance and varying load conditions.

When a photovoltaic (PV) module is linked to a load, the resultant output voltage (V), current (I), and power (P) depend on the operational state of the PV module. Different types of loads display unique I-V and P-V characteristic curves, with each PV module having its own distinctive I-V and P-V characteristic curve.

Figure 1 illustrates a generalized P-V and I-V characteristic curve for a PV module, which aids in identifying a specific operational point where maximum power output is achieved, known as the maximum power point (MPP). In the P-V characteristic curve, point A corresponds to the Maximum Power Point (MPP), aligning precisely with point B on the V-I characteristic curve.

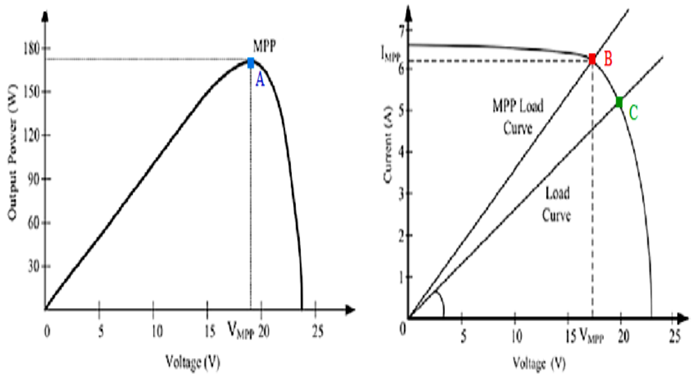

Fig. 1 - Generalized P-V and I-V characteristic curve of PV module

2.1 Perturb and Observe (P&O) MPPT

The Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) method is utilized to establish the most suitable duty cycle. This technique involves perturbing the operating point of the photovoltaic (PV) system and monitoring the subsequent variation in PV power output. To adapt to these changes, the algorithm modifies the reference voltage, denoted as Vref, by adjusting the duty cycle. A visual representation of the P&O method is presented in Figure 2, which outlines the algorithm's process.

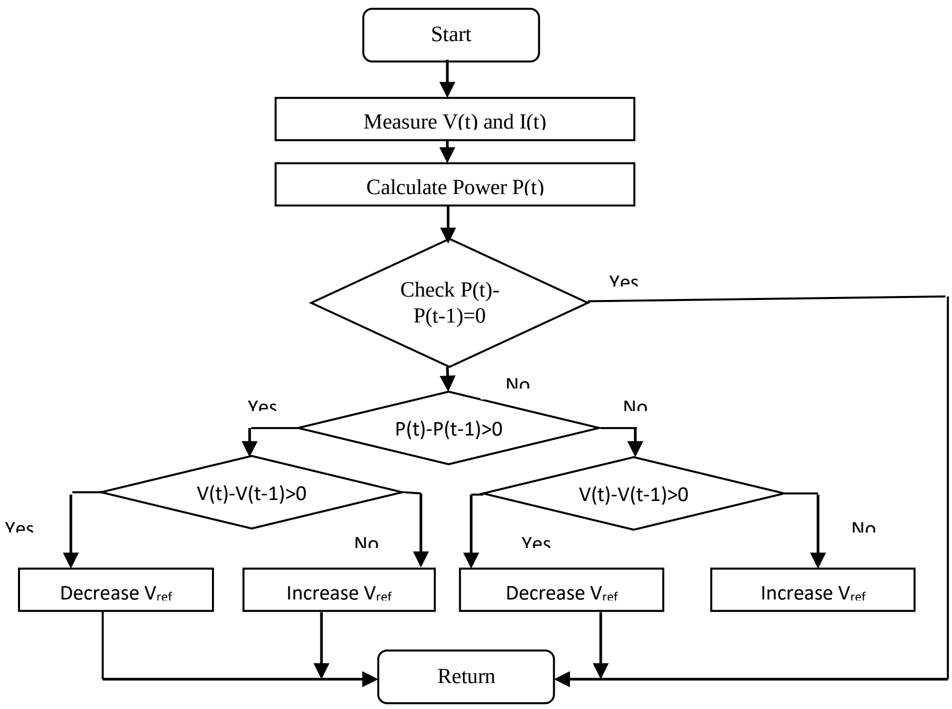

Fig. 2 - Flowchart of P&O method

2.2 Cascaded H-Bridge Multilevel Inverter

A cascaded H-bridge multilevel inverter represents a multilevel inverter design that involves the connection of numerous H-bridge modules in a series configuration, resulting in the generation of a superior quality output voltage waveform, as depicted in Figure 4. Within this cascaded arrangement, each H-bridge module typically consists of four power switches, as visually demonstrated in Figure 3.

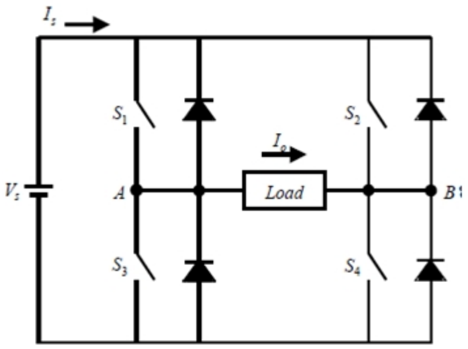

Fig. 3 - Basic building block of cascaded H-bridge multilevel inverter

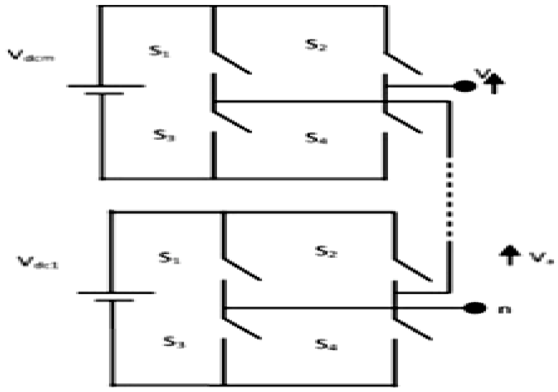

Fig. 4 - Multiple H-bridge modules connected in series

The operation of a cascaded H-bridge multilevel inverter involves the precise control of the switching states within the H-bridge modules to synthesize a stepped output voltage waveform. The quantity of voltage levels or steps within the output waveform corresponds directly to the number of H-bridge modules integrated into the cascaded configuration. Each H-bridge module contributes its unique voltage level, and the total number of levels depends on the quantity of modules used.

By manipulating the distinct voltage levels offered by each H-bridge module, a multilevel output voltage can be generated. This output exhibits reduced harmonic content and an improved waveform quality when compared to conventional two-level inverters. Cascaded H-bridge multilevel inverters find widespread application in scenarios demanding high-power conversion and superior power quality, including renewable energy systems, motor drives, grid-connected systems, and high-voltage applications.

2.3 Fuzzy Logic Controller

Fuzzy logic draws inspiration from the human reasoning process and involves the following stages:

a). Fuzzification: It converts crisp input data into linguistic fuzzy information or membership functions.

b). Inference: A set of IF-THEN statements makes decisions in intermediate stages, with the best option being chosen when dealing with ambiguous data.

c). Defuzzification: In this stage, a reverse process takes place in comparison to the first stage. Fuzzy data is transformed into a numerical value using membership functions.

Figure 5 illustrates the various phases within a fuzzy logic controller.

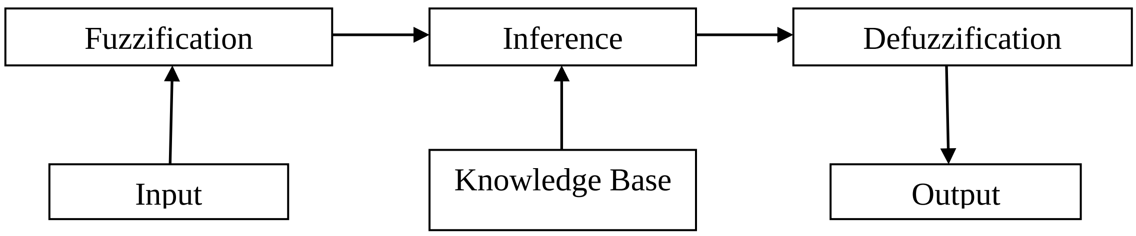

Fig. 5 - Block diagram of Fuzzy Logic Controller

2.4 ANN Controller

The concept of an Artificial Neural Network (ANN) is grounded in the functioning of the human brain. It models the structure of biological neural networks through mathematical modeling. Figure 6 shows the basic building block of an ANN.

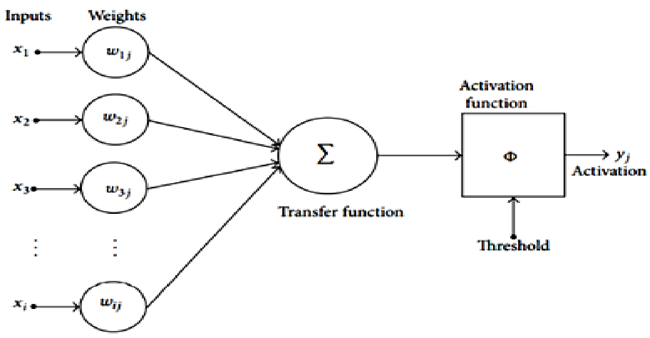

Fig. 6 - Representation of an Artificial Neuron

To enhance accuracy, the control algorithm necessitates a wide-ranging database obtained from the controller's input section. This database is employed to train the control algorithm. Neural networks collectively perform functions in parallel, and the neural network-based controller offers optimal voltage regulation for the input-output dataset.

The formula $V_{error} = V_{ref} - V_{actual}$ calculates voltage error values.

The Artificial Neural Network (ANN) is trained using these error values to determine the optimal switching angles for the inverter circuit, ensuring a consistent output voltage within acceptable error signal levels. The training process for the ANN comprises the following stages:

a) Input-output data set provisioning.

b) Weight calculations.

c) Weight adjustments based on input variations.

The neural network undergoes training using a diverse set of samples at various intervals to effectively process the error signal.

3. Simulation Study for Comparitive Analyis

A MATLAB Simulink model is employed to examine the performance and control strategies of a cascaded H-bridge multilevel inverter. Several strategies have been explored in the study to enhance power output and quality of solar PV systems. Fuzzy logic controllers and ANN are combined with MPPT for improved power output to optimize controllers for quality power output.

The investigation involves the utilization of the Fuzzy Logic Toolbox, Neural Networks Toolbox, and FFT Toolbox within MATLAB. Through MATLAB Simulink simulations, a comparative analysis is conducted between a controller based on fuzzy logic and one based on artificial neural networks (ANN), with a focus on evaluating their impact on total harmonic distortion (THD).

In Figure 7, a fundamental PV module is depicted, while Figure 8 illustrates a basic H-bridge. The simulation model incorporates multiple instances of PV modules and H-bridges.

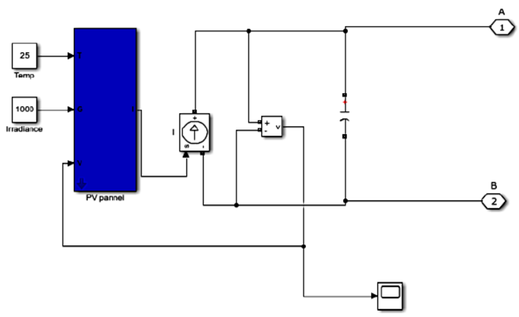

Fig 7 - MATLAB/Simulink Implementation of PV Module

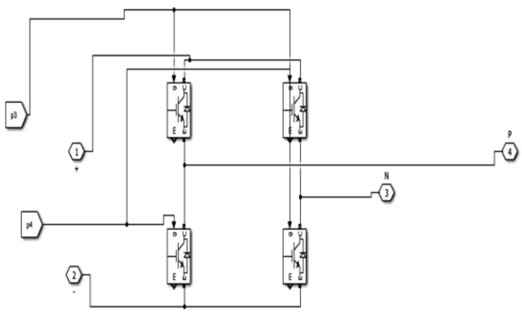

Fig 8 - MATLAB/Simulink Implementation of H Bridge

Figure 9 displays the MATLAB/Simulink realization of a 15-level cascaded H-bridge multilevel inverter. This multilevel inverter structure, powered by solar energy, serves as the foundation for simulating both the fuzzy logic-based controller and the ANN-based controller models.

The generation of pulses is accomplished using a bipolar Pulse-Double Pulse Width Modulation (PDPWM) technique. More specifically, it involves the comparison of a triangular wave with a positive sinusoidal signal for one leg, while the other leg includes a comparison between a triangular wave and a negative sinusoidal signal. You can observe this process in Figure 10.

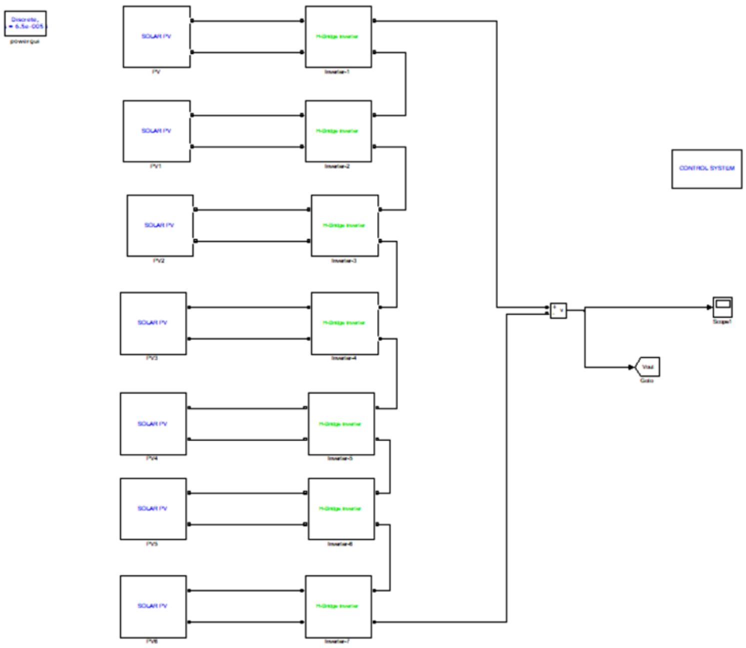

Fig. 9 - MATLAB/Simulink implementation of a 15-level cascaded H-bridge multilevel inverter

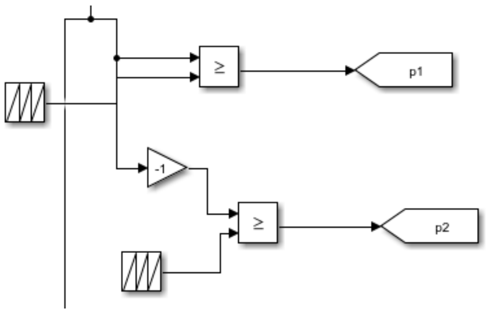

Fig. 10 - MATLAB/Simulink implementation of Bipolar Pulse-Double Pulse Width Modulation Method

4. Results and Discussion

The PV system examined in this study comprises seven H-bridges connected in series, forming a 15-level cascaded H-bridge multilevel inverter. This inverter configuration is designed to accommodate multiple inputs from the PV modules, enabling independent voltage control and maximum power point tracking (MPPT) for each string. To facilitate MPPT, the Perturb and Observe algorithm is implemented, dynamically adjusting the operating point of each PV module in response to changes in irradiance and temperature. Given the slight variations in characteristics among the PV panels, individual control and MPPT are essential for optimal performance.

For pulse signal generation, a bipolar pulse-width modulation (PWM) scheme is employed. This scheme involves the comparison of a reference signal, typically a sinusoidal waveform, with a triangular carrier signal to generate the necessary pulses for the multilevel inverter's switching operation. The bipolar PWM scheme ensures precise control of the output voltage waveform and facilitates efficient power conversion.

The incorporation of these features, including the cascaded H-bridge configuration, individual control, and MPPT for each string, as well as the use of bipolar PWM for pulse signal generation, aims to enhance power generation, improve efficiency, and optimize overall system performance.

In Figure 11, voltage waveforms generated using a Fuzzy Logic-based Controller are presented, while Figure 12 displays voltage waveforms generated using an ANN-based Controller. Both figures represent time in seconds on the x-axis and voltage in volts on the y-axis. Notably, both waveforms exhibit 15 levels within the generated waveform.

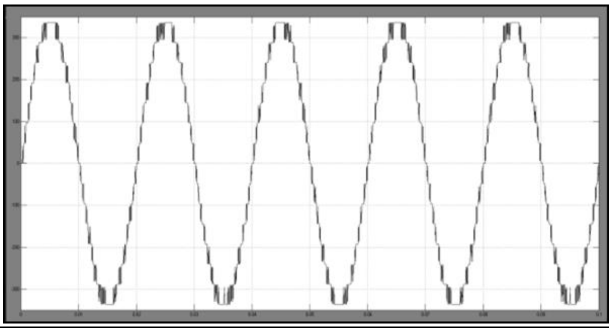

Fig. 11 - Simulated Voltage waveform using Fuzzy Logic Controller

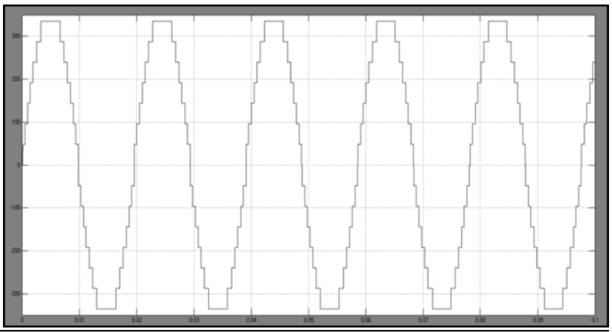

Fig. 12 - Simulated Voltage waveform using ANN

Total Harmonic Distortion (THD) quantifies the extent of harmonic distortion concerning the fundamental frequency of the signal. Evaluating THD is crucial for assessing power quality, as elevated levels of harmonic distortion can lead to issues like increased losses, reduced efficiency, equipment overheating, and interference with other electrical systems. By applying Fast Fourier Transform (FFT) to the output waveform, it becomes possible to identify and quantify the harmonic components present in the signal. This, in turn, allows for THD calculation, measuring the extent of harmonic distortion in the waveform.

Figure 13 illustrates the FFT analysis of the ANN-based controller, and Figure 14 displays the FFT analysis of the Fuzzy Logic-Based Controller.

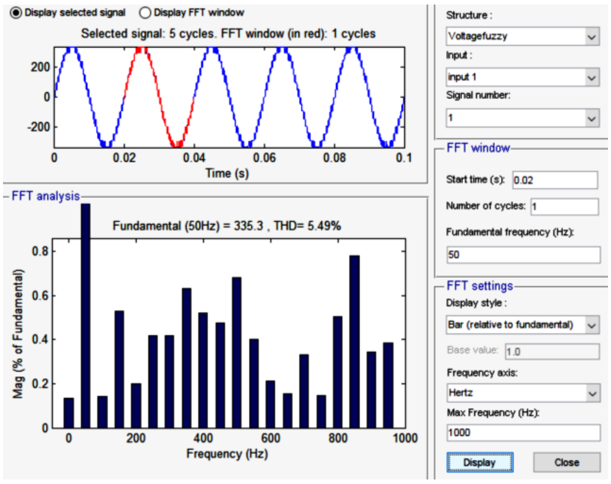

Fig. 13 - FFT Window representing THD for Fuzzy Logic Controller

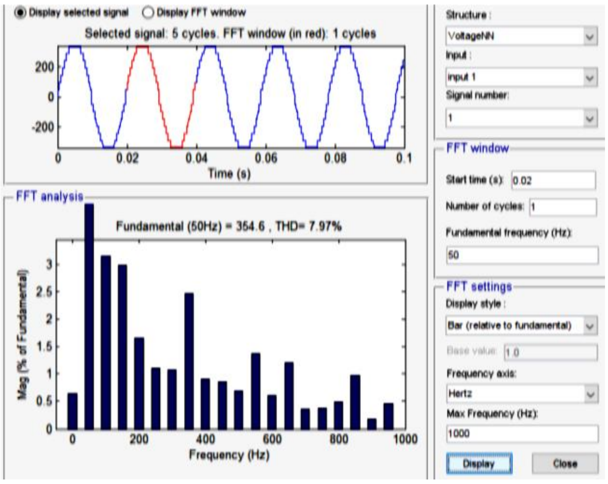

Fig. 14 - FFT Window representing THD for ANN based Controller

Table 1 provides a comparison of results. The table details the percentage of harmonic distortion and voltage levels present in the output waveform, as determined from the simulation results of each technique.

Table 1 - Comparison of results

Method	Voltage Levels	Total Harmonic Distortion
Fuzzy Logic based Controller	15	5.49 %
ANN based Controller	15	7.97 %

These results suggest that a lower THD percentage signifies a cleaner and more sinusoidal waveform with minimal harmonic distortions, indicative of improved power quality. The findings underscore the effectiveness of the Fuzzy Logic controller in reducing harmonic distortions and enhancing power quality within the studied system.

5. Conclusions

The research encompassed the effective realization of a 15-level cascaded H-bridge multilevel inverter powered by solar energy, accomplished using MATLAB/Simulink. Comparative analyses were performed via simulations, with a specific emphasis on controllers utilizing Fuzzy Logic (FLC) and Artificial Neural Networks (ANN).

The results reveal that the Fuzzy Logic Controller demonstrated superior voltage regulation, effectively handling fluctuations in the PV module inputs. The FLC also achieved a lower Total Harmonic Distortion (THD) percentage, indicating its capacity to generate a cleaner and more stable output voltage waveform. This contributes to the enhancement of power quality within the system, making it suitable for applications requiring grid integration and improved power quality.

These findings underscore the effectiveness of FLC in adapting to changing solar conditions and maintaining stable voltage levels in the inverter system. This preliminary study paves the way for more efficient and reliable utilization of renewable energy sources.

In terms of future research directions, several possibilities for enhancing power quality in PV systems are considered. Suggestions include exploring hybrid control strategies, investigating real-time operational scenarios with experimental validation, integrating with the grid, and enhancing cost-effectiveness and scalability.

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