ISSN PRINT 2319 1775 Online 2320 7876

 UGC CARE Listed (Group -I) Journal Volume 11 , Iss 1, Jan 2022

Solar Fed Cascaded Multilevel Inverter with Output Voltage Regulation

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ABSTRACT
The presence of harmonics in solar Photo Voltaic (PV) energy conversion system results in deterioration of power quality. To address such issue, this paper aims to investigate the elimination of harmonics in a solar fed cascaded fifteen level inverter with aid of Proportional Integral (PI), Artificial Neural Network (ANN) and Fuzzy Logic (FL) based controllers. Unlike other techniques, the proposed FLC based approach helps in obtaining reduced harmonic distortions that intend to an enhancement in power quality. In addition to the power quality improvement, this paper also proposed to provide output voltage regulation in terms of maintaining voltage and frequency at the inverter output end in compatible with the grid connection requirements. The simulations are performed in the MATLAB / Simulink environment for solar fed cascaded 15 level inverter incorporating PI, ANN and FL based controllers. To exhibit the proposed technique, a 3 kWp photovoltaic plant coupled to multilevel inverter is designed and hardware is demonstrated. All the three techniques are experimentally investigated with the measurement of power quality metrics along with establishing output voltage regulation.

INDEX TERMS: Harmonics, Intelligent Control, Multilevel Inverter, Photo Voltaic's, Power Quality,Voltage Regulation.

1. INTRODUCTION

Providing electrical energy access to rural zones is a fundamental requirement as a means of improving sustainable living standards topping the agenda in many developing countries [1]-[4]. Energy efficiency, electricity supply and sustainability are the most important research topics in society. The energy that is sustainable, renewable, cost-effective, reliable and secure is the fundamental requirement for economic growth, human and industrial development of a country. Ecological concerns, exhausting petroleum reserves and expanding reliance on fossil fuels from unstable locales have expanded the significance for more efficient use of energy. Sources like thermal, nuclear that has been used for some time now for the generation of electricity has its own merits and demerits. The developing attention to decrease the carbon footprint (CO2) has added to the expanding interest for research on non-fossil based fuel as a source of energy. Thus, a more sustainable energy supply is required across all sectors viz. residential, transportation, industrialisation and agriculture. This impromptu pressure and challenge on the environment have encouraged the energy providers to develop further and transform the energy system in a much effective manner. During the most recent times, it has been witnessed the reduced complexity of different energy policies and investment options are increased across the globe in the energy sector [5]. Renewable energy can be termed as liveliness from unlimited natural resources. There are many sources of natural renewable energy resource like sunlight, water, air, biomass, and geothermal heat. Over a specified

ISSN PRINT 2319 1775 Online 2320 7876

 UGC CARE Listed (Group -I) Journal Volume 11 , Iss 1, Jan 2022

geographical area, the scope and opportunities for renewable energy resources are vast in contrast to other forms of energy like fossil fuels that are limited and concentrated to specific localities. With the rapid deployment of renewable energy, efficiency, economic benefits are immense and would result in significant energy security, while reducing the environmental effects. This include positive developments in improved healthcare and reduction in infant mortality rates due to reduced pollution effect and countries would save millions on healthcare [6]-[8]. Renewable energy often displaces convention energy requirements in generation of electricity, water heating, transportation, energy services at rural areas (off grid). Along these lines, it can securely be expected that renewable energy assets go about as an impetus to increment and improve energy access in rural areas [9]. Solar energy is harnessed from the sun using PV technologies, solar heating, concentrated solar power, concentrated photovoltaics and are generally characterised based on the way the energy is captured, converted and distributed. They are either classified as active or passive. A PV system converts light into electrical energy taking advantage of the photoelectric effect. The PV system involves an array of silicon semiconductors that collect the photons and changes over to electrons. The generated DC is then convereted to AC using converters. Therefore, it is essential to utilize specific MPPT system to maximise the energy captured from the sun. This is generally achieved by using sun-tracking PV's. The sun-tracking PV's achieve this goal by adjusting itself to the global solar insolation shifts and amplifies the captured sunlight radiation to generate maximum power at a steady voltage. Efficiency in the solar array is estimated by the capacity to change over daylight into energy and is an exceptionally unique factor in picking the right panel for the PV system. As a reliable RE source, solar PV's can be successfully integrated into the mainstream power supply. However, there are many challenges in the solar energy system in the form of mismatch of the generated power from the PV and the demand. This is primarily due to the stochastic generation in PV. It leads to numerous other challenges, and one such problem is voltage regulation. Voltage in transmission and distribution over the years has been regulated by the use of active and reactive powers. Voltage regulation is the measure of the change in voltage between two endpoints that is between transmission and distribution. STATCOMs and SVCs are few devices that collaborate and ensures the voltage across is maintained within the permissible limits under load conditions [10]. The root cause for voltage regulation problems is mainly due to the presence of impedance leading either overvoltage or drops below normal under heavy load conditions. To alleviate the voltage imbalance, a power electronic interface is suggested between the source and load whose function is to provide output voltage regulation and also improving power quality. The novelty of the proposed work is to make use of multilevel inverter for providing the dual advantage. The term multilevel comes from the three level converters. The commutation of the semiconductor switches aggregates the multiple DC sources to achieve high output voltage levels. The advantages of multilevel inverters include improved quality of power, better electromagnetic compatibility, reduced losses in switches and enhanced voltage capability. The three structures of MLI are Neutral Point Clamped or Diode Clamped Multi Level Inverter, Flying Capacitor Multilevel Inverter and Cascaded Multilevel Inverter. In this paper, Cascaded Multilevel Inverter (CMLI) is utilized. The primary role of CMLI is to synthesize a preferred voltage from separate DC sources (SDCs) which may be obtained from batteries or solar cells. If the DC link voltages of the HBs are equal, then the CMLI is termed as symmetrical. As solar PV voltages are variable with respect to environmental factors, asymmetrical inverters are highly recommended. Asymmetrical inverters have unlike values of DC link voltages. Compared

IJFANS
International Journal of
Food And Nutritional Sciences
Official Publication of International Association of Food and Nutrition Scientists

ISSN PRINT 2319 1775 Online 2320 7876

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with other multilevel inverters, CMLI requires the least number of components to achieve the same number of voltage levels. The only disadvantage of the CMLI is that it needs separate DC sources for real power conversions. However this disadvantage can be compensated by utilizing solar PV at its input. Against this backdrop, the paper provides an elucidation to alleviate the voltage regulator control complexity and improve power quality in a solar power circuit.

2. PHOTOVOLTAIC

A PV cell is a simple p-n junction diode that converts the irradiation into electricity. Fig.3.2 illustrates a simple equivalent circuit diagram of a PV cell. This model consists of a current source which represents the generated current from PV cell, a diode in parallel with the current source, a shunt resistance, and a series resistance.

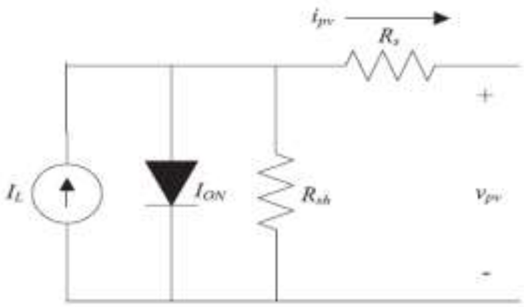

Fig. Equivalent circuit diagram of the PV cell

3. MULTI LEVEL INVERTER

An inverter is an electrical device that converts direct current (DC) to alternating current (AC) the converted AC can be at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. Static inverters have no moving parts and are used in a wide range of applications, from small switching power supplies in computers, to large electric utility high voltage direct current applications that transport bulk power. Inverters are commonly used to supply AC power from DC sources such as solar panels or batteries. The electrical inverter is a high power electronic oscillator. It is so named because early mechanical AC to DC converters were made to work in reverse, and thus were "inverted", to convert DC to AC.

Cascaded H-Bridges inverter

A single phase structure of an m-level cascaded inverter is illustrated in Figure 4.1. Each separate DC source (SDCS) is connected to a single phase full bridge, or H-bridge, inverter. Each inverter level can generate three different voltage outputs, $+V_{dc}$, 0, and $-V_{dc}$ by connecting the DC source to the ac output by different combinations of the four switches, S_1, S_2, S_3, and S_4. To obtain $+V_{dc}$, switches S_1 and S_4 are turned on, whereas $-V_{dc}$ can be obtained by turning on switches S_2 and S_3. By turning on S_1 and S_2 or S_3 and S_4, the output voltage is 0. The AC outputs of each of the different full bridge inverter levels are connected in series such that the synthesized voltage waveform is the sum of the inverter outputs. The number of

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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 4.2. The phase voltage

$$v_{an} = v_{a1} + v_{a2} + v_{a3} + v_{a4} + v_{a5} \quad \ldots(4.1)$$

For a stepped waveform such as the one depicted in Figure 4.2 with s steps, the Fourier Transform for this waveform follows

$$V(\omega t) = \frac{4V_{dc}}{\pi} \sum_n [\cos(n\theta_1) + \cos(n\theta_2) + \cdots + \cos(n\theta_s)] \frac{\sin(n\omega t)}{n}, \text{ where } n = 1,3,5,7 \ldots$$
$\ldots(4.2)$

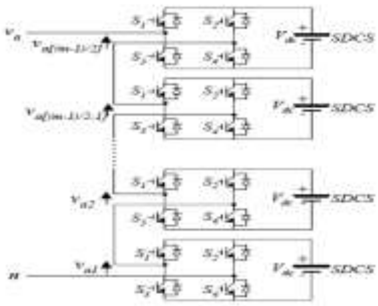

Fig.Single-phase structure of a multilevel cascaded H-bridges inverter

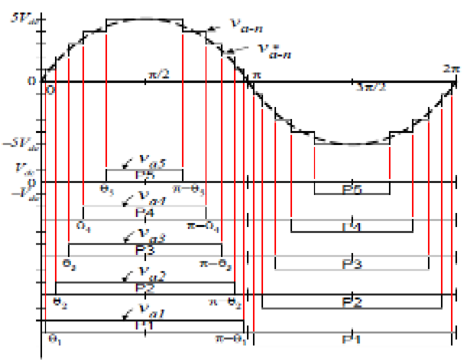

Fig. Output phase voltage waveform of an 11 level cascade inverter with 5 separate dc sources.

4. PROJECT DESCRIPTION AND CONTROL DESIGN

VOLTAGE REGULATION CONTROLLERS

In alternating circuits (AC) the load across the terminals need to be constant or adjustable. As the inverter in the solar power PV feeds into the terminal, the output voltage from the inverter needs to be controlled to meet the load in the AC circuits. Therefore, it is indispensable to ensure that deviations in the input DC voltage need to be compensated. This can be achieved

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on both DC and AC side with aid of controllers. PWM control can also be used for controlling the output voltage, which requires no external peripheral components. Unlike the conventional PWM schemes, modified PWM with advanced control topology is required to reduce the overall THD in improving the power quality. Besides, line and load regulation schemes to maintain the constant voltage can be performed whose expressions are given in Equations (1) and (2). However, these schemes are quite applicable to low power DC circuits.

Capacitor voltage balancing is extensively considered for maintaining the balanced DC input voltage for the multilevel inverters. But these methods are useful for DCMLI (Diode Clamped) and FCMLI (Flying Capacitor) topologies which prevents the wide acceptance of these inverters in practical applications. The major advantage of CMLI is that it has no unbalanced problems since isolated DC source (solar PV array) is fed in each DC link. In spite of this advantage, it poses a serious problem in maintaining a constant output voltage delivered to the consumers and also satisfying the grid connection codes. The magnitudes of the DC voltages at MPP are nearer to each other for PV modules possessing different irradiation or temperature. The usual variation is less than 15% and hence a suitable controller is required for the output voltage to be controlled at inverter end before it is fed to the consumers. The power quality improvement in inverters can be enhanced by many techniques. One way is to improve the power conversion with cascading the inverters, which results in lowering switching losses and improving power quality [11]- [12]. The resultant inverter power is then converted into high-voltage at a lower frequency and a reverse of lowvoltage at a higher frequency by cascading the inverters [13]. Corzine et al. demonstrated two three phase three level inverter with a single DC source with a resultant voltage THD of 9%. The popularity of the multilevel power converters led to numerous researchers contributing to its improvement. Some notable research carried out is indicated in table I. The renewable energy systems led to distributed generation systems coming into the picture with numerous households adopting to host solar power or micro-CHP and other technologies to sustain energy. As a result, the utility networks had to impose stricter standards to ensure power quality and protection from islanding and adapt to newer control strategies for reducing harmonics [14]. In this regard, Carrasco et al. surveyed new methods to improve power quality when integrating wind and PV generators and storage technologies [15]. In a bid to further reduce harmonic components in multilevel cascaded voltage source converters a new technique using Selective Harmonic Elimination Pulse Width Modulation (SHE-PWM) was tested on 3kVA prototype with an efficiency of 96% [16]. Mekihilef et al. proposed a new topology for the bidirectional power systems using multiple switches increasing its cost for implementation [17]. The associated cost with the converters is generally high when cascading them due to numerous switching components. The reduction in the components will not only bring down the components but also help in reducing losses. Babaei, therefore, proposed a series-connected sub-multilevel converter blocks with an aspire to trim down not only the number of components but also to reduce the installation surface area, switches, losses and the cost of the converter [18]. Daher et al. reviewed the various systems and used the technology to demonstrate on a stand-alone renewable energy system with 96% efficiency [19]. Abu-Rub et al. applied the principle on medium voltage with a focus to reduce harmonic distortion by increasing the power rating while minimizing and operating at low switching frequencies [20]. The basic purpose of the multilevel converter is to combine the inputs from numerous DC sources and synthesize it to ensure a proper output voltage which has minimum disturbances in the form of harmonics etc [21]. Beser et al.

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perfomed the experiment on single-phase multilevel inverter using various strategies for determining optimal switching angles to produce output voltage with lower THD and also elimination of required harmonic components [22]. Cecati et al. made an extensive study using Fuzzy Logic (FL) based controller. The FL based controller was put to use with H-bridge power sharing algorithm. 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 [23]. 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. Ahmadi et al. proposed a model based on criteria based four equation methods for multi and two level inverters. A study on weight oriented junction method for low level voltages is also undertaken [24]. Cavalcanti et al. tested a new modulation technique based on P-Q theory for three phase transformerless inverters for eliminating leakage currents in the PV systems employing multilayer cascading inverter configuration. The authors applied three, two and single vectors to increase system utilization and concluded that the system can provide greater MPPT and compensation for current harmonics and reactive power [25]. Most of the multilevel series converters are based on PWM methods. Cougo et al. applied this method 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 [26]. Anand et al. 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 CSI [27].

Controller Modelling

The inverter operations are identical and analogous to a generator or a synchronous machine to a grid and most renewable energy resources like solar PV are connected to a DS (Distribution System). Since the power generated in a PV varies due to the irradiation absorption on the panel, the rated voltage can vary anywhere from -20% to +20% during the day. With the use of power electronic circuits, it is possible to ensure a stabilized DC voltage in the PV. Since transmission of grid voltage is in AC, the stabilized DC voltage is then inverted to AC. In line with this, the proposed experiment uses a suitable inverter with a maximum variation of 1% to ensure accuracy for a 48V, 7A solar panel with a ±20% variation. A. FUZZY LOGIC CONTROLLER Lofti A. Zadeh put-forth the fuzzy logic, which is utterly different from Boolean algebra. The inherent characteristics of fuzzy logic are the values state has to be either 1 (ON) or 0 (OFF). The fuzzy logic varies from the Boolean logic due to its ability to accept two or more values between the true and false. Unlike the Boolean logic it accepts only true or false. Fuzzy logic helps in obtaining fixed conclusions from ambiguous, vague and imprecise information. The structure of the Fuzzy Logic Controller (FLC) used for performing VR in a solar PV fed cascaded H bridge multilevel inverter is exposed in Figure 1. Here, the output voltage (Vo) obtained from a fifteen level inverter output is then compared with the reference voltage (Vref), which is the preferred voltage to be achieved for the inverter in accordance with the grid requirements. The subsequent error, e = Vref− Vo and the rate of error change de/dt serves as input attributes for the FLC. The FLC consists of five major block set. They are fuzzifier, defuzzifier, inference system, rule base and database. Fuzzification in membership functions

ISSN PRINT 2319 1775 Online 2320 7876

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converts input data into degrees of membership. The commanding signal (or control signal) Cs obtained by the FLC is then contrasted with Vef to generate the modulating signal Ms required for PWM (pulse width modulation) generation, thereby afford the suitable gating signals to the semiconductor switches in the inverter power circuit.

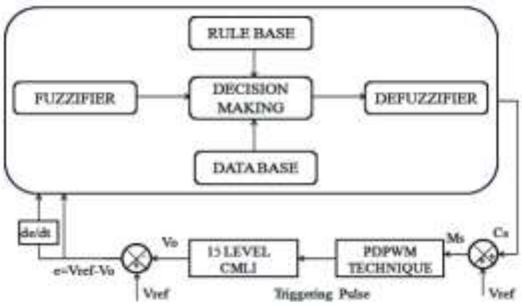

FIGURE . Fuzzy logic Control Structure

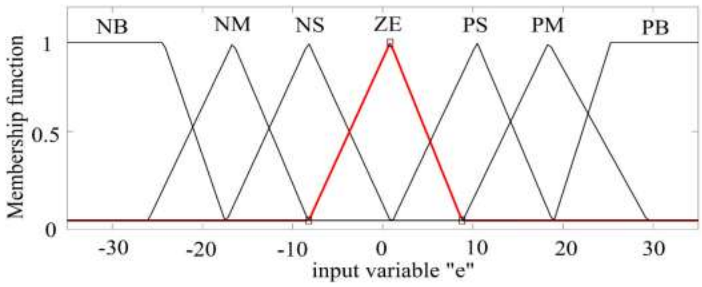

FIGURE 6.2. Membership function for error signal

The problem is formulated with an error and its derivative MF (membership function). The MF for the error signal is illustrated in Figure 6.2. In this figure, N indicates Negative, P for Positive and Z indicate Zero. Similarly, B indicates Big, M indicates Medium and S indicates small and E indicates the error. The derivative of the error signal for the fuzzy logic controller input and its MF is given in Figure.

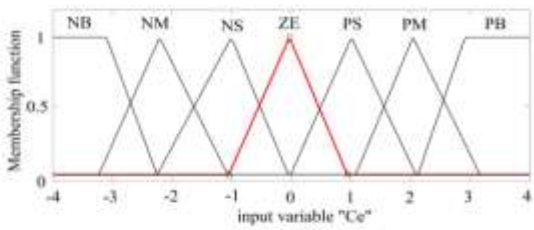

FIGURE. MF for the change in an error signal

Pi-Based Controller: As similar to the FLC, the role of PI (Proportional-Integral) controller is to maintain the output voltage of the inverter constant in accordance with the grid requirements. The PID controller has been widely used in all types of feedback system as shown in Figure 6. While the rules formulation and MF parameterization is the major task in FLC, in PI based controller, the tuning of controller gains is the major task to meet the

IJFANS International Journal of Food And Nutritional Sciences

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required objective. The PI controller gain is tuned for various error signals concerning the variable irradiance. The PI controller

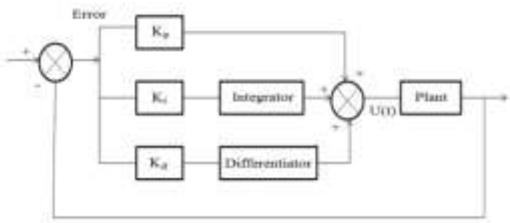

Fig: Structure of PID Controller

Artificial Neural Network Based Controller

Neural networks collectively perform functions and by the units parallelly, rather than there being a clear delineation of subtasks to which various units are assigned. Pertaining to the input-output dataset, the neural networks based controller provides the required voltage regulation. The voltage error values are calculated using this equation Verror = Vref – Vactual. These error values are used to train the ANN. For the appropriate values of error signals the ANN can provide the optimal switching angles for the inverter circuit to maintain the constant voltage at its output end. The training procedure of ANN consists of the following steps: 1) Provide the inputoutput 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.

5. SIMULATION AND ANALYSIS

The several DC links are featured in multilevel converters for making the independent control of possible voltage and MPP tracking at each string. A solar fed 15 level inverter without VR is an open-loop system. The panels with different irradiance level are designed and connected to each separate stages of CMLI. For the fifteen levels, seven cascaded Hbridges are connected in series. For the pulse generation, a reference and carrier signal is compared. The reference sinusoidal and the triangular carrier are compared for generating a pulse signal. The bipolar PDPWM technique is adopted for the pulse generation. For one leg, triangular wave and positive sinusoidal signal are compared, for the other leg triangular wave and negative sinusoidal signal are compared for pulse sequence. Figure 7 shows the modelling of PV panel with variations in the irradiance levels depicting the alteration in an inverter output voltage. Figure 8 depicts output voltage waveform obtained due to the variations in irradiance and partially shaded conditions of solar PV modules. 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.

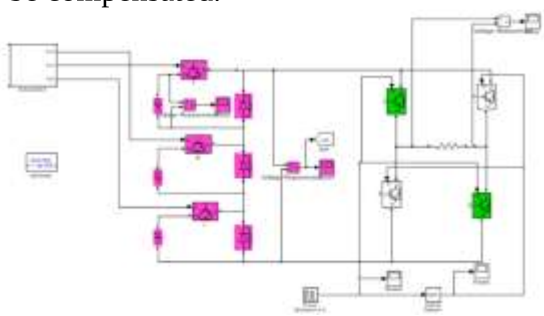

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Fig: Proposed simulation diagram

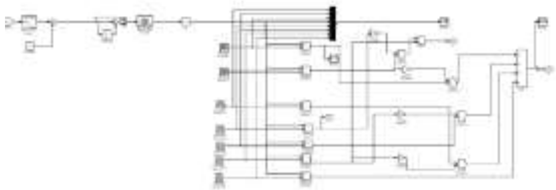

Fig: Fuzzy Controller

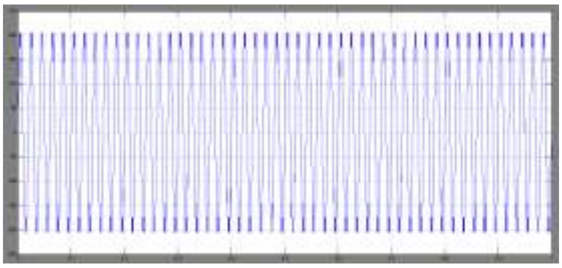

Fig: 15-level output based on fuzzy logic

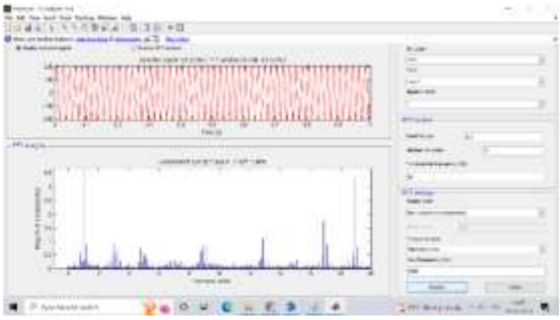

Fig: THD output based on Fuzzy

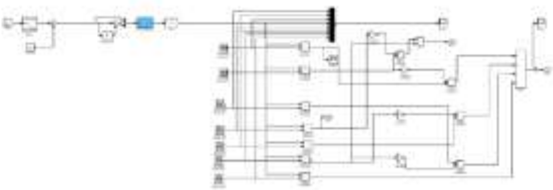

Fig: ANN Based Controller

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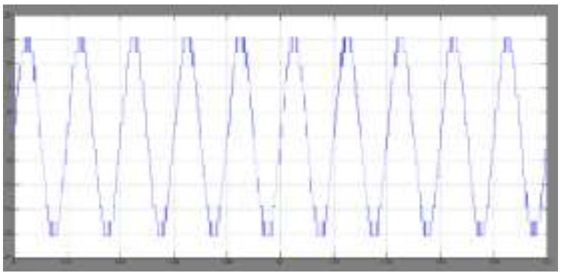

Fig: 15-level output based on ann

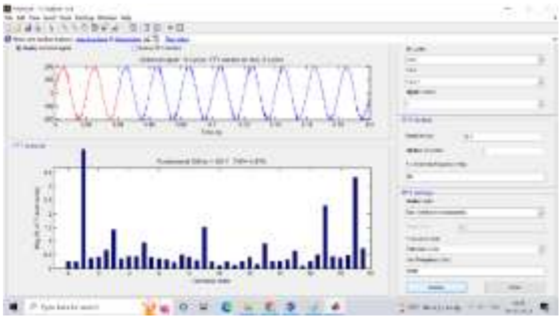

Fig: ANN based THD value

6. CONCLUSION

The voltage regulation topology along with power quality improvement is considered and implemented both in simulation and experimental setup for a solar fed 15 level inverter. While considering the results, it is found that FLC presents better results for VR while considering the variations at the input solar PV. Despite this, FLC is considered for the nine-level by [23], but the implementation is carried out with the DC power supplies without utilizing the solar panels. All the other methods are implemented for low power and lesser levels of MLI topology. Commercial utilization of MLI by providing the constant output voltage is investigated, and the experimental results prove the effectiveness of the proposed system. The method is applicable for the users require grid interaction along with the power quality improvement.

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