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Power Quality Improvement in Solar Fed Cascaded Multilevel Inverter with Output Voltage Regulation Techniques

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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

I. 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 (CO_2) 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 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 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. Section two reviews various techniques used in voltage control. Section three discusses the proposed methods for the proposed system, while section four discusses the results, and lastly section five concludes the research.

II. 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 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.

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$$\text{Line regulation} = \frac{(\Delta V_{out} / V_{out})}{\Delta V_{in}} \times 100\% \tag{1}$$

$$\text{Load regulation} = \left(\frac{V_{NOLOAD} - V_{FULLLOAD}}{V_{FULLLLOAD}} \right) \times 100\% \tag{2}$$

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 low-voltage 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 bi-directional 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. 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].

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Table 1 – Literature Review

Year	Study	Area / Results / Conclusion	Ref.
2019	Balanced Power distribution	Output voltage regulation with aid of closed loop operation	[36]
2019	Programmable Multilevel CSI	Reduced number of switches topology	[37]
2018	Comparative analysis	Using switched capacitor unit for 17 level inverter	[38]
2019	SHE-PWM	Reduced number of switches topology	[39]
2020	Binary hybrid multilevel inverter	Damped SOGI control	[40]
2020	Three phase MLI	Reduced number of switches topology	[41]
2019	Boost inverter	Reduced number of switches topology	[42]
2019	Switch ladder modified H bridge MLI	Power quality improvement with pulse width modulation	[43]
2019	Reduced switch count	Power quality improvement with pulse width modulation	[44]
2020	Reduced switch count	Review and analysis	[45]
2020	Energy balancing	Isolated multi Modular Multilevel inverter	[46]
2020	Multilevel dual buck inverter	Adjustable discontinuous modulation	[47]
2020	Reliability improvement	Phase shifted PWM scheme	[48]
2020	Zero leakage current for grid tied inverter	Transformerless five level inverter	[49]

Chavarria et al. 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 [28].

In [29], 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 transformerless grid-connected system reference [30] proposed a new model of synthesizing upto 9 voltage levels for improving the common mode leakage current and regulating voltage in the flying capacitor [30].

The doubling of the output voltage level can improve the power quality in the inverter systems. This strategy was tested by Chattopadhyay et al. 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 [31].

In grid-tied PV systems, the use of inverters as interface go ahead to stability and safety issues while also leading lower efficiency. In a bid to progress the effectiveness of the system, Taleb et al. simulated a new strategy for controlling and switching operations. They used a hysteresis controller for enhancing the current delivered by power inverter ensuring no additional requirements of DC-DC voltage controller and power filters [32]. The proposed system results in superior power quality while preventing harmonics. Dynamic active compensation system was developed and simulated using MATLAB by Dash et al. for achieving reactive power compensation, which results in effective power quality improvement when variable generation systems are interconnected [33]. The grid-connected renewable energy (RE) source plays a dual role i.e. providing active power during the daytime and vice-versa, which in turn compensates the reactive power and harmonic distortion. In [34], the P-Q issues concerning distributed generation systems were discussed in detail by incorporating various P-Q devices. This detailed study includes the power quality improvement for the systems with DC and renewable sources. With respect to RE sources, the best choice can be STATCOM due to its advantages over traditional systems. Frequency Adaptive Notch Filter (FANF) based control algorithm was anticipated by [34] and incorporated to single phase grid interfaced WEGS for improving the power quality, which is mainly used for extracting the fundamental component of load current. This system mainly focuses on supplying the active power to loads along with grid and mitigation of power quality issues takes place at the same time.

Mortezaei et al. in their study compared various grid connected inverters namely, shunt, series and hybrid with two inverters for a better understanding of harmonics. They designed a hybrid system with one inverter and the performance was compared with the existing methods. The kVA rating of the inverters are compared with voltage quality problems. Besides, the power electronic circuit was compared based on the number of switches, inverters, functionalities and control complexity [35]. Gupta et al. studied the Maximum Constant Boost Control (MCBC) for an impedance source inverter incorporating Fuzzy logic (FL) based for a grid connected PV with a view of enhancing system stability [36]. Conservative Power Theory (CPT) for multiple master slave islanded microgrid for enhancing the quality of power was proposed by Mosalam et al. The inverters presented in the nearby proximity operate together in the master slave mode. Control signals are communicated between inverters to afford immediate load allocation comeback for mitigating objectionable current components of nonlinear or unbalanced loads [37]. An intelligent hybrid control algorithm was tested by Choi et al. [38] for integrating the solar PV system in the smart grid environment

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since an effective control system is required for synchronization. The algorithm follows cos ϕ technique plus Quasi Newton Back Propagation (QNBP) neural network for better performance. This helps in feeding the power to the utility grid, eliminating harmonics, power factor correction (PFC) and zero voltage regulation modes in improving power quality. The system incorporated with the proposed algorithm provides faster response during dynamic and static conditions.

Chaudhary et al. simulated a 750 kW (SPV farm – 250 kWp + WTG (Wind turbine generator) – 500 kWe) hybrid system using D-STATCOM (Static Synchronous Compensator) with a view to enhancing the quality of power in hybrid system. The shunt controller is proposed to reactive power absorption and delivering for voltage stability maintenance [39]. An improvised model was adapted by Parija et al. using a dual extractor third order signal integrator. The model was tested on weak grids using the integrated system (WEGS (Wind energy generation system) + PV) with an outlook to enhance the fundamental components of load current and grid voltage by separating them for synchronization with the grid [40]. This technique safeguards the entire system while mitigating various power quality issues like THD (Total Harmonic Distortion) and DC injection. For optimal power extraction, perturb and observe algorithm is implemented.

III. 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 (V_o) 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 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.

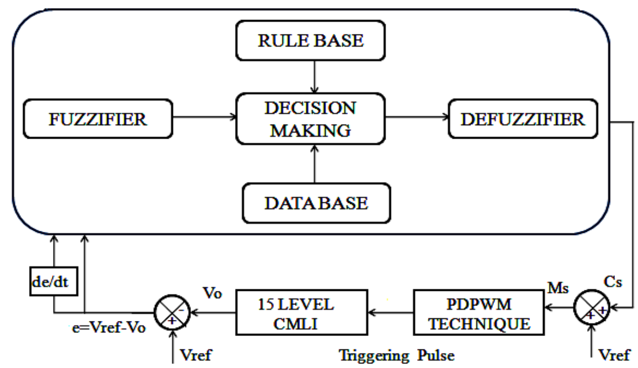

FIGURE 1. Fuzzy logic Control Structure

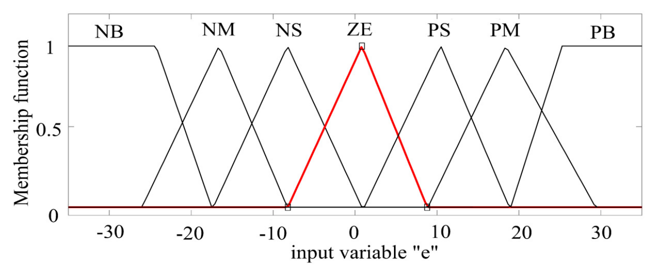

FIGURE 2. Membership function for error signal

The problem is formulated with an error and its derivative MF (membership function). The MF for the error signal is illustrated in Figure 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 3.

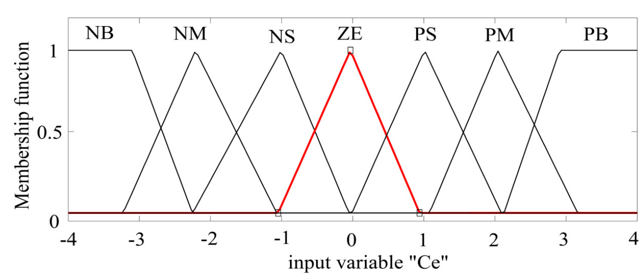

FIGURE 3. MF for the change in an error signal

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The fuzzy logic output is the reference signal formed from a membership function as shown in Figure 4. The rule table with two inputs (error and its derivative signal) and one output (reference signal) is framed as a rule matrix shown in Table II. The fuzzy value is then converted to crisp value using a defuzzification procedure. The method adopted for the conversion is Centre of Gravity (COG). The 3-D visualization of input error and its derivative with output reference signal are exposed in Figure 5.

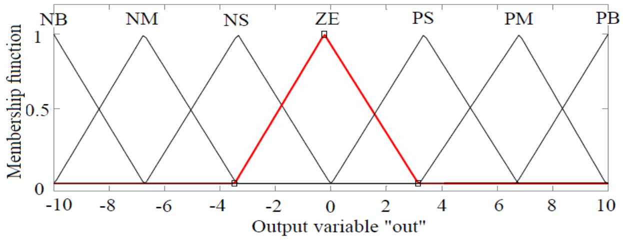

FIGURE 4. MF for the reference output

TABLE II
FLC RULE MATRIX

Ce \ e	NB	NS	NM	ZE	PB	PS	PM
NB	PB	PB	PB	PB	ZE	PM	PS
NS	PB	PM	PB	PS	NM	ZE	NS
NM	PB	PB	PB	PM	NS	PS	ZE
ZE	PB	PS	PM	ZE	NB	NS	NM
PB	ZE	NM	NS	NB	NB	NB	NB
PS	PM	ZE	PS	NS	NB	NM	NB
PM	PS	NS	ZE	NM	NB	NB	NB

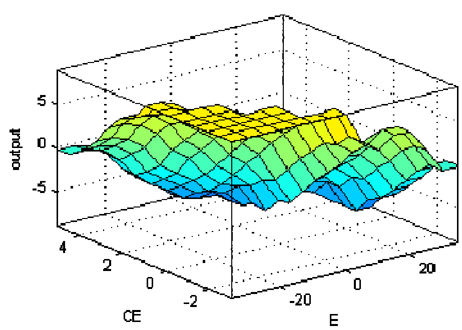

FIGURE 5. 3 D visualization of Fuzzy rules

B. 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 required objective.

The PI controller gain is tuned for various error signals concerning the variable irradiance. The PI controller generates reference signal for the various error signal received due to the variations in the input solar PV. The PI controller gain is tuned for various error signals concerning variations in irradiance. The PI controller generates reference signal for the various error signal generated due to the variations in the solar PV. The PI controller is tuned manually for different error values for output voltage regulation by considering the real time solar data for the geographical region considered and listed in Table III.

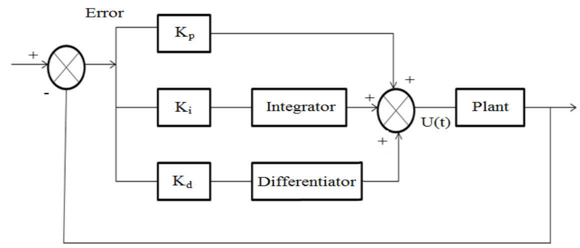

FIGURE 6 Structure of PID Controller

TABLE III
TUNED VALUES FOR PI CONTROLLER FOR VOLTAGE REGULATION

K_p	K_i	Output peak voltage (V_p)
0.355	0.5	315.8
0.1	0.5	322.4
. .	. .	. .
0.05	0.2	323.7
0.45	0.2	313.35
0.6	0.3	309.5
0.2	0.3	320
0.03	0.3	324
0.01	0.5	325
. .	. .	. .
0.03	0.1	324.2

C. 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 $V_{error} = V_{ref} - V_{actual}$. 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 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.

IV. 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 H-bridges 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.

A. FIFTEEN LEVEL INVERTER WITH PI-BASED CONTROLLER

The DC input of CMLI changes according to the irradiance. The measured voltage value of solar fed CML1 across the load is evaluated with the desired signal. The error signal is obtained and applied as the input to PI based controller. The gain values, Kp=0.04 and K_i=0.5 is used for the PI based controller. The control signal from the PI controller output is further mixed with the reference signal to obtain the overall revised signal required for pulse generation. On receiving the required pulse signal, the regulated output voltage thus obtained is shown in Figure 9 and the FFT (Fast Fourier Transform) assessment is shown in Figure 10.

B. ANN BASED CONTROLLER FOR FIFTEEN LEVEL INVERTER

The specifications considered for the voltage regulation in solar fed 15 level inverter using ANN is shown in the Table IV. The regulated output voltage is shown in Figure 11 and the corresponding FFT analysis in Figure 12.

C. FIFTEEN LEVEL INVERTER WITH FUZZY LOGIC CONTROLLER

The decision and pattern making is achieved by using Fuzzy inference. The error and derivate error signal are the two inputs signals and framed as membership function. Triangular membership function is used in the controller. The membership function produces a modulating output signal for the PWM generator. The error and derivative error each have 7 membership functions. Nearly 49 rules are framed and used for the better voltage regulation. The regulated output voltage is exposed in Figure 13 and the corresponding FFT analysis in Figure 14.

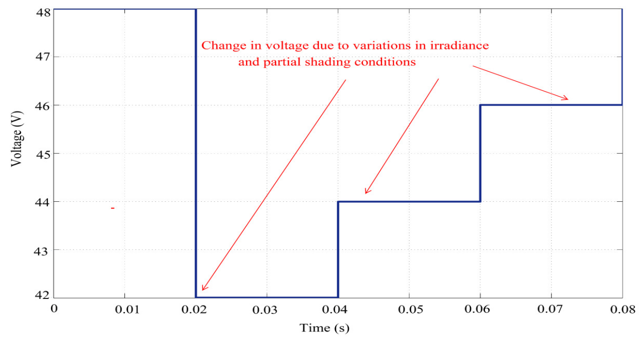

FIGURE 7. Variation of output voltage with respect of irradiance

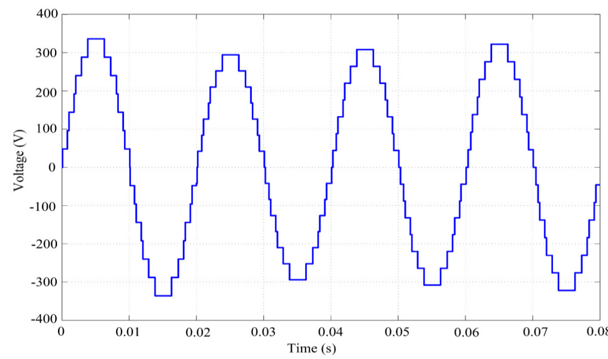

FIGURE 8. Fifteen level output voltage with variable irradiance

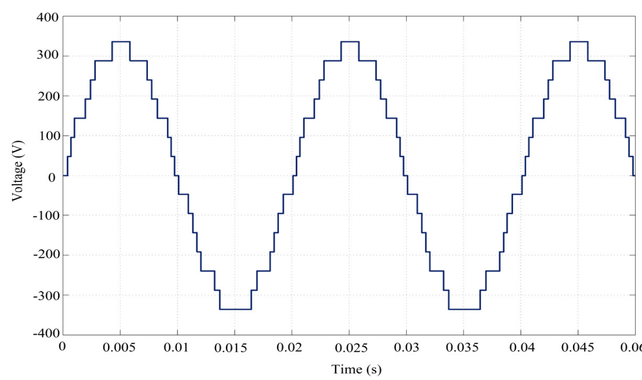

FIGURE 9. Regulated fifteen level output voltage with PI controller

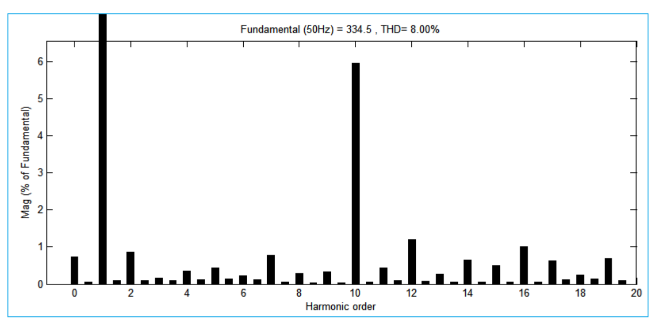

FIGURE 10. FFT analysis for PI based voltage regulation

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TABLE IV
SPECIFICATION FOR ARTIFICIAL NEURAL NETWORK

Parameters	Functions
Input layer numbers	2
Hidden layer numbers	10
Output layer numbers	1
Network	Back Propagation
Algorithm	Gradient Descent
Learning rate	0.05
Goal	$1e^{-5}$
Iteration count	3000
Training function	Purelin
Activation function	Sigmoid & Tangential

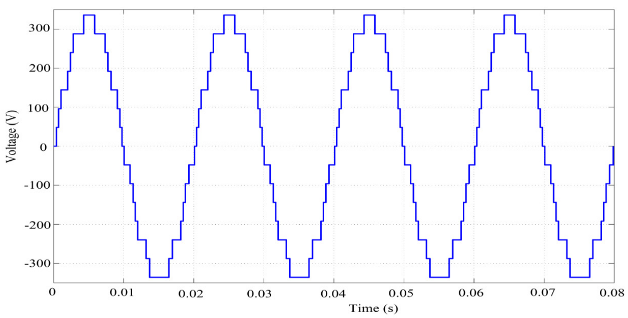

FIGURE 11. Regulated fifteen level output with ANN based controller

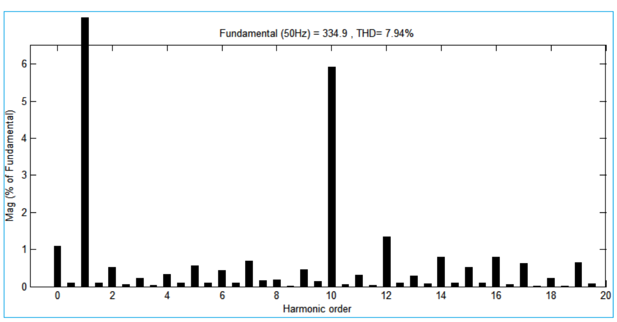

FIGURE 12. FFT analysis for ANN based voltage regulation

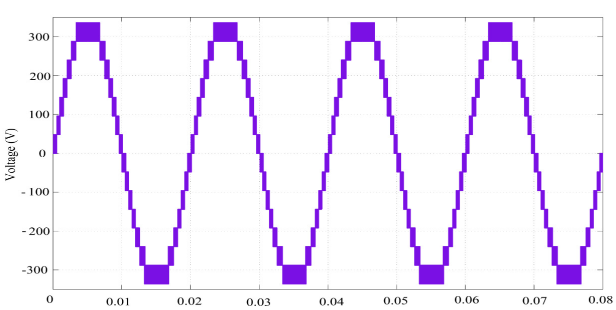

FIGURE 13. Regulated fifteen level output voltage with FLC

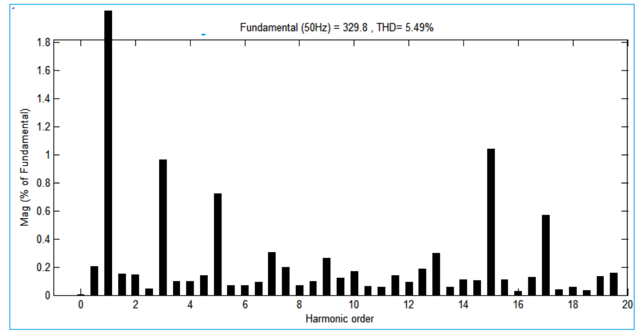

FIGURE 14. FFT analysis for FLC based voltage regulation

V. EXPERIMENTAL INVESTIGATION

A 3kWp solar PV plant is taken into consideration to achieve voltage regulation in a 7 stage 15 level inverter. Individual inverter ratings are 48V, 7A. The single solar module rated power is 115W, while 28 modules are used. The voltage is varying between 16 to 21 volts based on the light intensity. The storage battery with the rating of the 12V, 100Ah and 4 of them are attached in series configuration. The detailed system specifications are given in Table 5. The output nominal DC bus voltage is 48Volts. While measuring voltage across the battery set up, the variation is recorded in the range of 37V to 58V. This variation causes uneven voltage distribution at the output end of the inverter. Hence the microcontroller ATMEGA 16AVR is used to perform the VR in the solar fed CMLI. The required voltage is scaled down to the suitable limits for comparison with the actual value obtained. Based on this, the compensating signal required for the pulse generation is created. These pulses are given to the MOSFET switches through an optocoupler, and the corresponding VR is achieved. The Figure 15 shows the experimental setup for the solar fed fifteen level inverter.

The Figure 16 shows the integration of the inverter with the solar PV system. The output waveforms for open loop and closed loop are shown in Figure 17 and Figure 18 respectively. For the different conditions, the output waveforms are obtained and analysed.

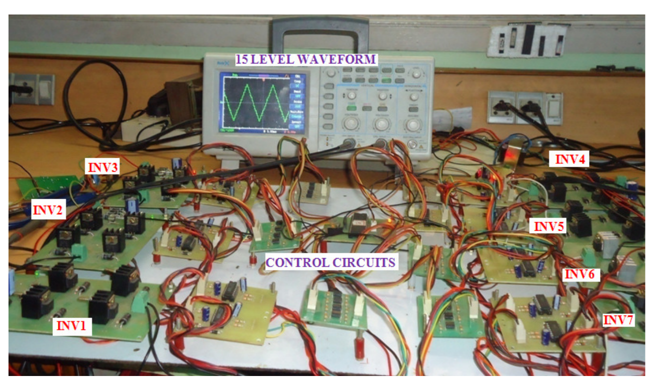

FIGURE 15. Experimental setup for fifteen level inverter with VR

TABLE V
SYSTEM SPECIFICATIONS

Solar PV Model	Solectric 9000
Pmpp	115Wp – 28 numbers
Vpm	16.5V
Ipm	6.95A
Voc	21.2V
Isc	7.4A
Max system voltage	540V
Tolerance at peak power	±5%
Total power	3220Wp (3kWp)
Charge Controllers	Sukaam (48V,10A) – 7 numbers
Battery	EXIDE 6LMS100L (12V, 100Ah) - 28 numbers
Switch	MOSFET IRF840
Controller	ATMEGA 16AVR

Figures 19-21 conveys the analysis of output voltage and current waveforms, which depict all the parameters required for regulation. The Figure 21 depicts the waveform in isolated operation and not under the grid connected mode. The objective of the converter is to provide the required voltage and current in compatible with the grid requirements; while the realistic grid connected operation is not undertaken in the study.

Power quality investigation is conceded with the PQA WT3000 and the THD results are shown in Figure 22. Table VI shows the comparison of various controllers for output VR, in which FLC gives better results in regulating the voltage when compared to PI and ANN-based controllers.

Table VII shows the comparison of results with other methodologies. As only a limited number of works are reported for the VR, the comparison was made with respect to methodology adopted and the number of levels considered.

One of the drawbacks of the closed loop system is stability which is the time delay due to the comparison of actual and desired signals to generate error and then reducing the error in controller block set. In order to make sure the reduction in delay taken in the feedback process without any mismatch a dead time of 1μs is introduced in the controller.

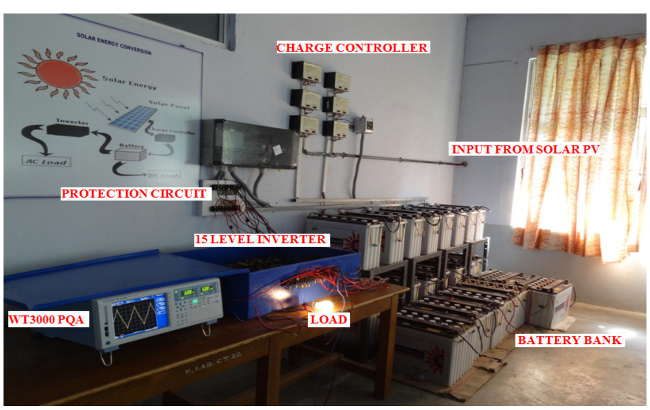

FIGURE 16. Integration of the proposed inverter with solar PV

FIGURE 17 Regulated output waveform for voltage in open loop condition

FIGURE 18. Regulated output waveform for voltage in closed loop condition

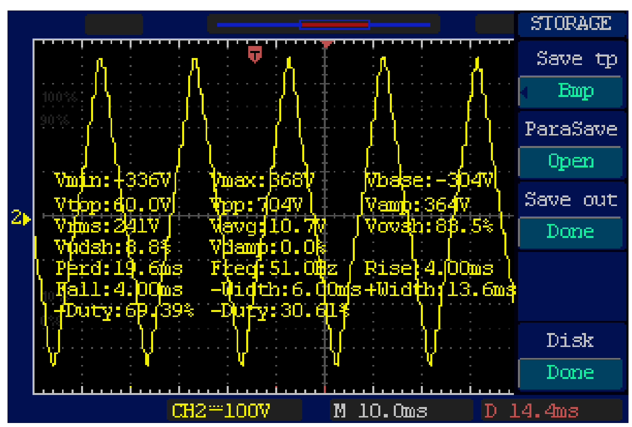

FIGURE 19. Waveform analysis for output voltage (V_{RMS}=241V)

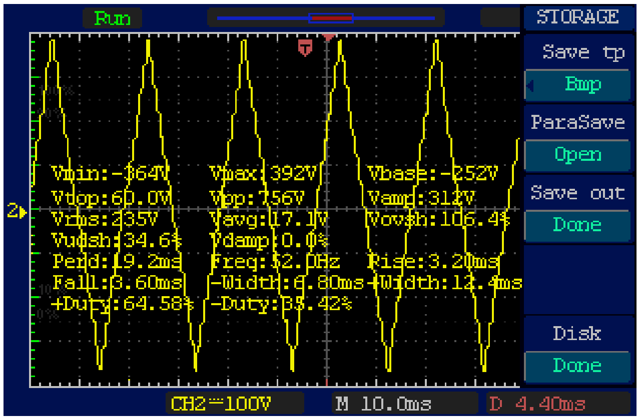

FIGURE 20. Waveform analysis for output voltage (V_{RMS}=235V)

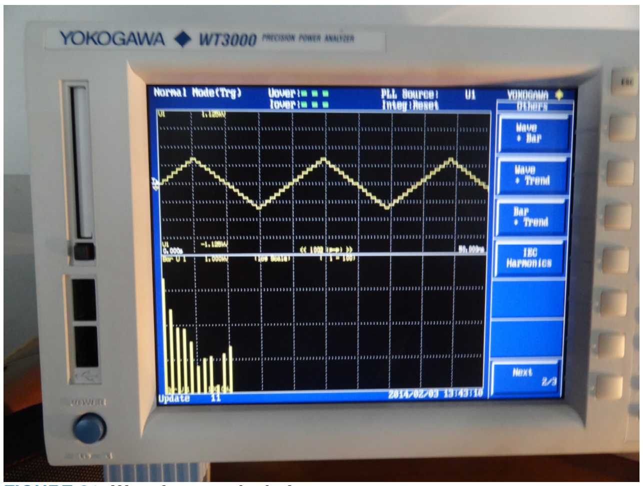

FIGURE 21. Waveform analysis for output current

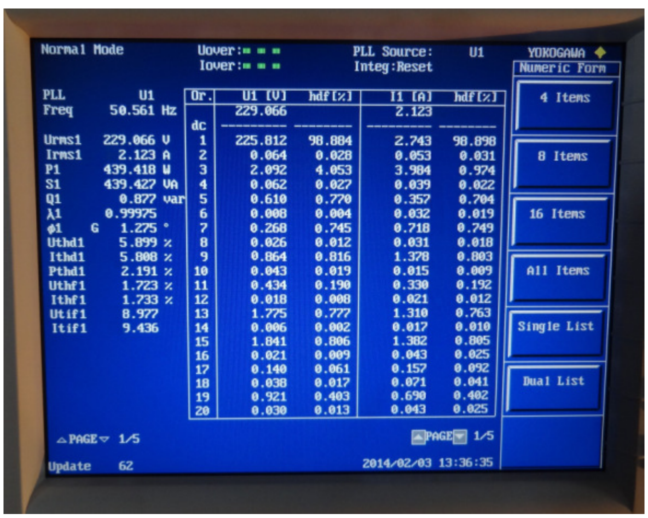

FIGURE 22. Output voltage waveform PQ analysis

TABLE VI
COMPARISON OF RESULTS

S.No.	Method	Level	THD	VR deviation
1	PI	15	8 %	9.3
2	ANN	15	7.94 %	9.7
4	FLC	15	5.49 %	4.6

TABLE VII
COMPARISON OF RESULTS WITH OTHER METHODOLOGIES

S.No.	Authors	Levels	Methodology	THD
1.	Jeyraj & Rahim (2009) [50]	5	PI	6.8 %
2	Ghazanfari et al (2012) [51]	5	Voltage balancing	6.13 %
3	Cecati et al (2010) [23]	9	Fuzzy	-
4.	Corzine et al (2004) [13]	7	PI	9 %
5.	Proposed	15	Fuzzy	5.9 %

VI. 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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