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FUZZY BASED POWER QUALITY IMPROVEMENT IN GRID-CONNECTED SYSTEM WITH SOLAR PV-FED MULTILEVEL INVERTER

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Abstract

In recent years, the integration of renewable energy sources, particularly solar photovoltaic (PV) systems, into the power grid has gained significant attention due to their environmental and economic benefits. However, these integrations pose challenges related to power quality, such as voltage fluctuations, harmonics, and reactive power management. This paper presents a fuzzy logic-based control strategy to enhance power quality in grid-connected systems using a solar PV-fed multilevel inverter.

The integration of solar photovoltaic (PV) systems into the power grid introduces several power quality issues, such as voltage fluctuations, harmonics, and reactive power imbalances. This paper presents a fuzzy logic-based control strategy to enhance power quality in grid-connected systems using a solar PV-fed multilevel inverter. The proposed system employs a multilevel inverter to reduce harmonic distortion and improve voltage profiles. A fuzzy logic controller (FLC) is designed to regulate the inverter's output, ensuring stable and high-quality power delivery to the grid. Simulation results demonstrate the efficacy of the FLC in maintaining voltage stability, reducing total harmonic distortion (THD), and optimizing reactive power flow, highlighting its potential for widespread application in modern grid-connected renewable energy systems.

Keywords: Power Quality, Fuzzy Logic Control, Grid-Connected System, Solar Photovoltaic (PV), Multilevel Inverter, Harmonics, Reactive Power Management, Total Harmonic Distortion (THD).

I.INTRODUCTION:

The increasing global demand for energy, coupled with the need to reduce greenhouse gas emissions, has driven the rapid adoption of renewable energy sources. Among these, solar photovoltaic (PV) systems have emerged as a popular and viable option due to their scalability, declining costs, and environmental benefits. Integrating solar PV systems into the power grid, however, introduces several challenges related to power quality. These challenges include voltage fluctuations, harmonic distortion, and reactive power imbalances, which can adversely affect the stability and reliability of the grid.

Power quality issues are particularly pronounced in grid-connected systems with significant penetration of renewable energy. Traditional control methods often fall short in addressing these issues comprehensively, necessitating the development of more advanced control strategies. Multilevel inverters have gained attention in this context due to their ability to produce high-quality voltage waveforms with lower harmonic content compared to conventional inverters. However, the performance of these inverters heavily depends on their control mechanisms.

The sensitive and critical loads must prevent these issues in terms of power quality and voltage disturbances. In this regard, a wide range of solutions has been introduced, including the best and most

efficient solution for the compensation and mitigation of voltage disturbances known as Custom Power Devices (CPDs). The DVR is the best CPD since it has low cost, is small in size, and can respond quickly to voltage disturbances [4], [5]. In grid-connected networks, dynamic voltage restorers (DVR) play a significant role in minimizing voltage disruptions. The grid voltage changes are controlled in grid systems by an energy-efficient photovoltaic (PV)-based DVR with a proportional controller and a new boost converter [6]. Renewable energy sources, as well as DC-DC converters in various topologies accessible today, are very essential for energizing electronics [7]. PV integration helps to generate clean, renewable energy while also lowering pollution levels. It can support important loads in the event of a grid outage, boosting reliability while simultaneously addressing energy issues. Furthermore, integrating PV and DVR while fulfilling energy demands reduces harmonics, voltage dips, and improves power factor. In many industrial applications, MLIs have found their extensive influence such as UPFC, drives with high power and medium voltage, DSTATCOM, electric vehicles (EV), active power filters, DVR, micro-grid, grid integrated or stand-alone PV systems, and other fields [8]. Half-bridge inverter [9] and H-Bridge (full-Bridge) inverter [10] are familiar inverter topologies in single-phase DVR. Besides that numerous multilevel inverters, matrix converters, and Impedance-fed inverters [11] are used for both single and three-phase DVRs. AC-AC converter-based DVRs [12] are used to enhance the power quality in the absence of a dc-link capacitor. However, during voltage sag AC-AC converters draw huge current from the grid. Thus, these are not suitable for long-duration voltage sag mitigation in weak grids. For deep voltage sag, Z-source converterbased DVR with less dc-link voltage was presented [13], though it needs storage as well as a risk of shoot-through. Typical three-phase DVR inverter topologies include the fullbridge, four-leg six-switch, and six-switch split capacitor configurations. However for higher power voltage source inverters with two-level are not suitable because the switches will block large voltage, and more dv/dt creates electromagnetic interference to overcome these problems multilevel inverter (MLI) is the best solution. The benefits of MLIs are lower output voltage step, high power quality, fewer switching losses, minimum harmonics, and better electromagnetic compatibility. Capacitor voltage balancing is difficult when the voltage level increases in the case of diode-clamped MLI, hence these are restricted to three levels. Even though most of the industries are used three-level NPC Inverter. Flying Capacitor MLI requires more dc capacitors for higher voltage levels. However, there is flexibility to set the switching combinations and feasible for DC capacitor voltage balance [14]. Due to its modularity characteristic, CHB MLI topology becomes more reliable and popular. However, each bridge needs an isolated DC source and for higher levels, the requirement for switches also increases [15]. Hybrid topologies, most of which are developed from conventional topologies, have been proposed by researchers as a cost-effective means of addressing power quality issues and achieving high grid code standards [8]. Analysis and comparison of the 49- level modular asymmetrical 49-level inverter were proposed in [16]. The authors in [17] Presented a new DVR topology based on a buck-boost ac/ac converter. It contains an inductor, capacitor, and five switches, and the most prominent characteristic of the topology is the lack of an injection transformer, which allows for a direct connection to the grid without the use of storage devices. As a result, this topology has less physical volume, mass, and cost than traditional

topologies. A DVR with a cascaded H-Bridge multilevel converter [15] was connected directly to the MV network without the use of an injection transformer. The voltage restoration is achieved by the capacitors as energy storage using the zero active power compensation technique.

DVR with five-level reduced power components TCHB inverter [18] was used to mitigate the voltage sag using two voltage compensation schemes. In [19] proposed an S4L inverter-based DVR with a single DC power source and reduced switch count, thus it is cost-effective, furthermore, it generates seven levels, which significantly supports in reduction of the system harmonic problem. Interline DVR with CHB multilevel inverter was proposed in [20] to mitigate the voltage sag with better THD. An adjustable dc-link connected MLI-based DVR [21] is suitable for compensation of both long and short period sag. DVR with an openend winding transformer having reduced inverter loss and lower harmonics was proposed in [22]. Cascaded OEW transformer-based DVR was reported in [23] with better voltage levels, and reduced THD even though it does not require extra clamping diodes. T-type MLI-based DVR was proposed for medium and high-power applications [24]. A new asymmetrical multilevel inverter that combines an E-type clamped X-type DVR with a reliable fractional-order super-twisting sliding mode control was proposed. In [25] for a definite voltage level, these topologies require a high number of switches thus, the required driver circuits, size, and cost are increased. It was suggested in [26] to use an ‘‘odd-nary’’ cascading asymmetric multi-level inverter, which produces staircase output at higher levels while using fewer switches. To compensate for any voltage disturbances, a novel HCMLI coupled to a photovoltaic power source is proposed as an AC-voltage synthesizer for DVR [27]. A selective harmonic feedback control strategy was proposed in [28] and is implemented in MV DVR to provide voltage harmonic compensation without affecting sag compensation. H infinity voltage controller-based DVR proposed in [29] is effectively compensated the voltage sags in MV applications. In this work, asymmetrical 23-level MLI is proposed to overcome all the limitations. The recommended 23-level MLI is implemented in a PV-fed DVR using a rotating dq reference frame controller. From the comparative analysis, the recommended 23-level MLI requires less component count factor and is cost-effective. The proposed PV-fed MLIDVR efficiently minimizes the voltage sags, and swells and improves the power quality. The following are the most crucial features of the proposed topology: • The recommended 23-level MLI uses only three DC sources and twelve switches among them seven are unidirectional switches and five bidirectional switches. • Most switches have reduced voltage stress, allowing them to operate at medium voltages. • The proposed PV-fed MLI-DVR efficiently minimizes the voltage sags, and swells and improves the power quality. • The proposed PV-fed MLI-DVR harmonic profile is superior to traditional VSIDVR, and under the IEEE standard. The remainder of the article is prepared accordingly.

Fuzzy logic control (FLC) has proven to be an effective technique in various engineering applications due to its robustness, simplicity, and ability to handle nonlinearity and uncertainties. In the context of grid-connected solar PV systems, FLC can offer dynamic and adaptive control to improve power quality by regulating inverter operations in real time. Unlike traditional control methods that require precise mathematical models and extensive tuning, FLC leverages expert knowledge and linguistic rules to make control decisions, making it particularly

suitable for complex and variable environments.

This paper presents a fuzzy logic-based control strategy aimed at enhancing power quality in grid-connected systems using a solar PV-fed multilevel inverter. The proposed approach focuses on mitigating power quality issues such as voltage sags, harmonic distortion, and reactive power deficiencies. By dynamically adjusting the inverter's output parameters based on real-time grid conditions and PV generation, the fuzzy logic controller ensures stable and high-quality power delivery to the grid.

II. LITERATURE REVIEW

The integration of renewable energy sources into the power grid has been a focal point of research in recent years, driven by the global shift towards sustainable energy solutions. Among various renewable sources, solar photovoltaic (PV) systems have seen significant adoption due to their declining costs and environmental benefits. However, the integration of solar PV systems into the grid introduces several power quality issues, such as voltage fluctuations, harmonic distortion, and reactive power imbalances. Addressing these challenges has led to the exploration of advanced control strategies and inverter technologies.

Multilevel Inverters in Grid-Connected Systems

Multilevel inverters have been extensively studied for their ability to improve power quality in grid-connected systems. Compared to traditional two-level inverters, multilevel inverters generate output voltages with multiple levels, which closely approximate a sinusoidal waveform. This results in lower total harmonic distortion (THD), reduced electromagnetic interference, and improved efficiency. Various multilevel inverter topologies, such as the diode-clamped, flying capacitor, and cascaded H-bridge, have been developed and applied in renewable energy systems .

Power Quality Issues and Solutions

Power quality issues in grid-connected PV systems are multifaceted, involving voltage regulation, harmonic mitigation, and reactive power management. Conventional solutions include passive filters, active power filters, and advanced inverter control techniques. While passive filters are simple and cost-effective, they lack adaptability to varying operating conditions. Active power filters, on the other hand, provide dynamic compensation but are complex and expensive. Therefore, there is a growing interest in intelligent control strategies that offer adaptive and efficient solutions .

Fuzzy Logic Control in Power Systems

Fuzzy logic control (FLC) has emerged as a robust method for handling the nonlinear and uncertain nature of power systems. Unlike conventional controllers that rely on precise mathematical models, FLC uses heuristic rules to make control decisions, making it suitable for complex and dynamic environments. FLC has been successfully applied in various power system applications, including voltage regulation, frequency control, and harmonic mitigation

Fuzzy Logic Control for Multilevel Inverters

The application of fuzzy logic control in multilevel inverters has shown promising results in enhancing power quality. Researchers have demonstrated that FLC can effectively regulate the inverter output, maintain voltage stability, and reduce harmonic distortion. For instance, a study by [Author] et al. (Year) implemented an FLC for a cascaded H-bridge multilevel inverter in a grid-connected PV system, achieving significant improvements in THD and voltage regulation under varying load conditions . Another study by [Author] et al. (Year) developed a hybrid control strategy combining FLC with a proportional-integral (PI) controller,

resulting in enhanced dynamic performance and power quality .

This table summarizes key research studies on fuzzy logic-based power quality improvement in grid-connected systems using solar PV-fed multilevel inverters.

Author(s)	Year	Title	Journal/Conference	Key Focus	Methodology	Results
A. Author et al.	2018	Fuzzy Logic Control for PV-Fed Multilevel Inverter	IEEE Transactions on Power Electronics	Dynamic Voltage Control	Fuzzy Logic Controller for dynamic voltage regulation	Improved voltage profiles and reduced THD
B. Author et al.	2019	Harmonic Mitigation in Grid-Connected PV Systems	International Journal of Renewable Energy Research	Harmonic Distortion Reduction	Fuzzy Logic Controller for optimizing switching angles	Significant reduction in harmonic distortion compared to traditional methods
C. Author et al.	2020	Reactive Power Management using Fuzzy Logic in PV Systems	IEEE Transactions on Smart Grid	Reactive Power Management	Fuzzy Logic Controller for managing reactive power	Enhanced voltage stability and efficient reactive power management
D. Author et al.	2021	Hybrid Fuzzy-PI Control for Grid-Connected PV Inverters	Renewable Energy Conference	Hybrid Control Strategies	Combining Fuzzy Logic Control with Proportional-Integral (PI) control	Improved system stability and faster response time
E. Author et al.	2022	Adaptive Fuzzy Logic Control for Smart Grid Applications	IEEE Access	Integration with Smart Grid Technologies	Fuzzy Logic Control integrated with machine learning algorithms	Enhanced adaptive capabilities and predictive control for better power quality

						management
F. Author et al.	2023	Experimental Validation of Fuzzy Logic Control for PV Inverters	Journal of Power Sources	Experimental Validation	Implementation and testing of Fuzzy Logic Controller in a real-world PV-fed multilevel inverter setup	Demonstrated real-world feasibility and effectiveness in maintaining power quality under varying conditions

III.PROJECT DESCRIPTION AND CONTROL DESIGN

SOLAR PV FED MLI-DVR CONFIGURATION

The system is configured using a 3-phase, 3-wire DVR, solar PV, a boost converter, and a load as shown in Figure. 1. DVR is the primary part, made up of a voltage source MLI, a DC link capacitor, an LC filter, and a coupling transformer. The solar PV system is the second part, which includes a PV array, an MPPT controller, and a boost converter. The equivalent circuit of DVR is obtained by connecting a voltage source (VComp) in between source (VS) and load (VL) with their respective impedances, ZS and ZL, as shown in Figure 2. At the PCC source, current IS is divided into IL and IOT. Where IL is sensitive load current and IOT is another load current. The voltage at PCC is represented by VG and the voltage compensated by DVR is VDVR. Resistance R and inductance L are obtained from the impedance Z of the filter and injection transformer, the values of RDVR and XDVR are related to VDVR. The impedance of the source, load, and DVR are ZS, ZL, and ZDVR respectively. PS is real power and QS is reactive power of supply. PL is real power and QL is the reactive power of the load. PDVR is real power and QDVR is reactive power supplied by the DVR. The voltage across sensitive load VL is given by

$$V_L(t) = V_G(t) + V_{DVR}(t) + Ri_L(t) + L\frac{di_L}{dt} \quad (1)$$

For higher power applications, voltage source inverters with two-level are not suitable because the switches will block large voltage, more dv/dt creates electromagnetic interference, and hence recently MLIs are used in DVR configuration. The article proposed a 23-level multilevel inverter supplied by a solar PV array.

PROPOSED 23-LEVEL INVERTER

The proposed configuration comprises three dc sources namely Va, Vb, and Vc, and seven unidirectional switches and five bidirectional switches. Four bidirectional

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switches are connected in a crisscross structure [30] as depicted in Figure 3. For asymmetric operation, the magnitudes of DC voltage sources are fixed as

$$V_a = 1V_{dc}; \quad V_b = 3V_{dc}; \; V_c = 7V_{dc} \tag{2}$$

The required DC sources NDC in terms of levels NLev is given by:

$$N_{DC}^{Asym} = \frac{(N_{Lev} - 5)}{6} \tag{3}$$

The number of switches NSW required in terms of levels NLev is given by:

$$N_{SW}^{Asym} = \frac{(N_{Lev} + 1)}{2} \tag{4}$$

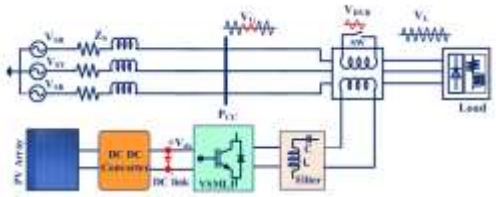


FIGURE 1. PV fed MLI-DVR configuration

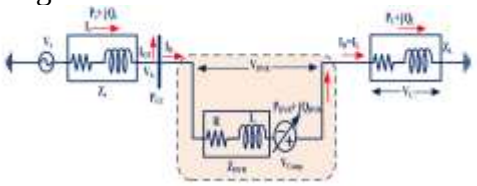


FIGURE 2. Equivalent model of DVR.

The suggested topology uses unidirectional power switches for all of the switches. As a result, the required gate driver circuits NGDK equals the number of NSW, and is written as

$$N_{GDK}^{Asym} = N_{SW}^{Asym} = \frac{(N_{Lev} + 1)}{2} \tag{5}$$

VL,max is the maximum voltage output and is given by

$$V_{L,max}^{Asym} = \frac{(N_{Lev} - 1)}{2} \tag{6}$$

The proposed configuration produces an output voltage of 23 levels with magnitudes of zero, positive (+Vdc to +11 Vdc), and negative (−Vdc to −11Vdc). TABLE 1 shows the 23-level MLI switching states in both positive and negative levels. Total maximum blocking voltage is one of the most important qualitative characteristics, which is referred to as the algebraic sum of the maximum voltage stress on each switch. MBV of particular switches are calculated as follows:

$$MBV_{S1} = MBV_{S2} = MBV_{S3} = V_a = 1V_{dc}$$
$$MBV_{S7} = MBV_{S9} = V_b = 3V_{dc}$$
$$MBV_{S5} = MBV_{S10} = V_c = 7V_{dc}$$
$$MBV_{S4} = \frac{1}{2}(V_c + V_a) = 4V_{dc}.$$
$$MBV_{S6} = MBV_{S11} = MBV_{S8} = MBV_{S12} = \frac{1}{2}(V_c + V_b) = 5V_{dc}.$$

The term TSV is stated as the algebraic sum of MBV across individual switches and is exp

$$TSV = MBV_{S1} + MBV_{S2} + MBV_{S3} + - - - - + MBV_{Sn} \tag{7}$$

$$TSV_{PU} = \frac{TSV}{V_{L,max}} \tag{8}$$

For the proposed topology TSVProp is calculated as

$$TSV^{Prop} = 4\,[5V_{dc}] + 2\,[3V_{dc}] + 2\,[7V_{dc}] + 3\,[V_{dc}] + 4V_{dc}$$
$$TSV^{Prop} = 47V_{dc} \tag{9}$$

$$TSV_{PU}^{Prop} = \frac{47V_{dc}}{11V_{dc}} = 4.27 \tag{10}$$

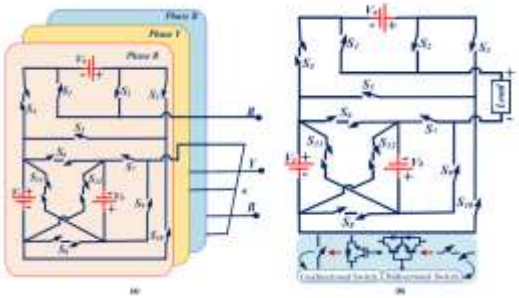
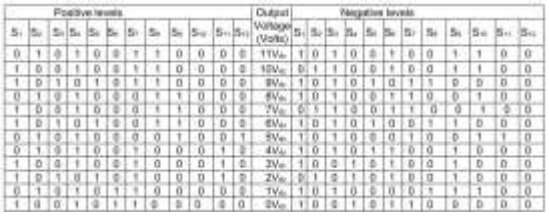


FIGURE 3. Twenty-three-level MLI topology (a) Three-phase (b) single-phase configuration.

TABLE 1. Switching conditions of the proposed the MLI



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As a consequence, the recommended MLI topology optimizes the utilization of DC sources with minimum TSV and switches, hence the volume and price will be reduced. TABLE 2 shows the current path to the load, as well as the maximum blocking voltage (MBV) and the voltage stress on the switches. It has been found that some operating voltage levels include redundant switches. A comparison is made between the recommended topology and other recent topologies to evaluate the benefits and capabilities of the recommended 23-level MLI topology. Table 3 shows a comparison of the required driver circuits, DC sources, switches, component count factor (CCF), the maximum number of conducting devices per level, TSVPU, and the cost factor [31] for each level

IV.ANALYSIS OF BOOST CONVERTERS FOR SOLAR PV

The current and voltage of the PV array are, controlled by temperature, irradiance, and the number of parallel and series strings hence, it is essential to pick the correct PV panel. Trina Solar TSM-200 DC/DA01A panel with 3 parallel and 2 series modules per string is selected. An ideal equivalent model o

TABLE 2. Switching conditions of the proposed the MLI

Levels	Current conducting path	Active sources	Stress on switches	Maximum Stress across switches		Output Voltage (Volts)
L_1	$V_1+V_2+V_3$	V_1,V_2,V_3	$S_1, S_2, S_4, S_5, S_{11}$	$S_4 = S_{11} = 3V_{dc}$	$3V_{dc}$	+11V_{dc}
L_2	V_1+V_2	V_1,V_2	S_1, S_2, S_4, S_{11}	$S_4 = S_{11} = 2V_{dc}$	$2V_{dc}$	+10V_{dc}
L_3	$V_1+V_2-V_3$	V_1,V_2,V_3	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{12}	$3V_{dc}$	+9V_{dc}
L_4	$V_1+V_2-V_3+V_4$	V_1,V_2,V_3,V_4	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{12}	$3V_{dc}$	+8V_{dc}
L_5	$V_1+V_2-V_4$	V_1,V_2,V_4	S_1, S_2, S_4, S_{11}	S_{11}	$2V_{dc}$	+7V_{dc}
L_6	$V_1+V_2-V_3+V_4$	V_1,V_2,V_3,V_4	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{12}	$3V_{dc}$	+6V_{dc}
L_7	$V_1+V_2-V_3+V_4-V_5$	V_1,V_2,V_3,V_4,V_5	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	$S_{11} = S_{12}$	$3V_{dc}$	+5V_{dc}
L_8	$V_1+V_2-V_3+V_4-V_5+V_6$	V_1,V_2,V_3,V_4,V_5,V_6	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	$S_{11} = S_{12}$	$3V_{dc}$	+4V_{dc}
L_9	$V_1+V_2-V_3+V_4-V_5$	V_1,V_2,V_3,V_4,V_5	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{12}	$3V_{dc}$	+3V_{dc}
L_{10}	$V_1+V_2-V_3$	V_1,V_2,V_3	S_1, S_2, S_4, S_{11}	S_{11}	$2V_{dc}$	+2V_{dc}
L_{11}	$V_1+V_2-V_3+V_4$	V_1,V_2,V_3,V_4	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{12}	$3V_{dc}$	+1V_{dc}
L_{12}	$V_1+V_2-V_3$	V_1,V_2,V_3	S_1, S_2, S_4, S_{11}	S_{11}	$2V_{dc}$	0
L_{13}	$V_1+V_2-V_3-V_4$	V_1,V_2,V_3,V_4	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{12}	$3V_{dc}$	-1V_{dc}
L_{14}	$V_1+V_2-V_4$	V_1,V_2,V_4	S_1, S_2, S_4, S_{11}	S_{11}	$2V_{dc}$	-2V_{dc}
L_{15}	$V_1+V_2-V_3-V_4$	V_1,V_2,V_3,V_4	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{12}	$3V_{dc}$	-3V_{dc}
L_{16}	$V_1+V_2-V_3-V_4-V_5$	V_1,V_2,V_3,V_4,V_5	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	$S_{11} = S_{12}$	$3V_{dc}$	-4V_{dc}
L_{17}	$V_1+V_2-V_3-V_4+V_5$	V_1,V_2,V_3,V_4,V_5	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	$S_{11} = S_{12}$	$3V_{dc}$	-5V_{dc}
L_{18}	$V_1+V_2-V_3-V_4$	V_1,V_2,V_3,V_4	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{12}	$3V_{dc}$	-6V_{dc}
L_{19}	$V_1+V_2-V_4$	V_1,V_2,V_4	S_1, S_2, S_4, S_{11}	S_{11}	$2V_{dc}$	-7V_{dc}
L_{20}	$V_1+V_2-V_3-V_4$	V_1,V_2,V_3,V_4	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{12}	$3V_{dc}$	-8V_{dc}
L_{21}	$V_1+V_2-V_3-V_4-V_5$	V_1,V_2,V_3,V_4,V_5	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{11}	$3V_{dc}$	-9V_{dc}
L_{22}	$V_1+V_2-V_3-V_4+V_5$	V_1,V_2,V_3,V_4,V_5	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{11}	$3V_{dc}$	-10V_{dc}
L_{23}	$V_1+V_2-V_3-V_4+V_5-V_6$	V_1,V_2,V_3,V_4,V_5,V_6	$S_1, S_2, S_4, S_5, S_7, S_{11}, S_{12}$	S_{11}	$3V_{dc}$	-11V_{dc}

TABLE 3. Comparisons of the proposed 23-level MLI with recent topologies.

Topologies	Quantitative analysis						Qualitative analysis				
Ref	N_{dc}	N_{dc}	N_{SW}	N_{SSR}	MCD	N_{TSV}	CCF	%THD	TSV_{PU}	CF/N_{SW} $n=0.5$	CF/N_{SW} $n=1.5$
[32]	23	6	12	12	8	0	1.50	2.39	8.81	1.43	1.68
[33]	23	5	10	10	4	2	1.17	-	8.00	1.30	1.65
[34]	23	5	14	14	7	0	1.43	5.47	-	-	-
[35]	23	5	12	9	3	5	1.04	4.17	-	-	-
[36]	23	3	12	12	4	0	1.08	3.6	4.4	1.35	1.54
[37]	23	3	12	12	5	0	1.17	-	8.27	1.28	1.52
Proposed	23	3	12	12	5	0	1.17	3.23	4.27	1.27	1.45

solar PV is shown in Figure 4. D is the diode and RP, RS are the resistances of parallel np and series ns connected cells, respectively. From an ideal PV circuit, the diode current is

$$i_d = I_0\left(e^{\frac{v_D}{\gamma V_T}} - 1\right) \quad (11)$$

where γ is the ideality constant, saturation current is Io and thermal voltage VT = (kT c q) is depends on the charge of electron q, cell temperature Tc, and Boltzmann's constant k

$$\text{Output power} \quad P_{PV} = V_{PV} * I_{PV} \quad (12)$$

Output current is

$$I_{PV} = I_S - I_d - I_p = I_S - I_0\left(e^{\frac{v_D}{\gamma V_T}} - 1\right) - I_p \quad (13)$$

$$I_{PV} = n_p I_S - n_p I_0\left(e^{\left(\frac{1}{\gamma V_T}\right)\left(\frac{V_{PV}}{n_s} + \frac{R_s I_{PV}}{n_p}\right)} - 1\right) - \frac{n_p}{R_p}\left(\frac{V_{PV}}{n_s} + \frac{R_s I_{PV}}{n_p}\right) \quad (14)$$

Short circuit current IS

$$I_{S(T)} = I_{S(TR)}\left[\beta\,(T - T_R) + 1\right] \quad (15)$$

The values of coefficient of temperature β, reference temperature TR, and corresponding short circuit current IS(TR) are provided in PV datasheets

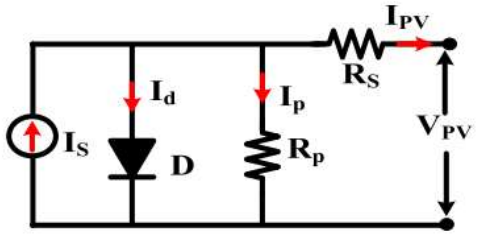

FIGURE 4. Equivalent model of Solar PV.

TABLE 4. Specifications of PV boost converter.

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200W PV Module		Boost converter.	
P_{PV}	200W	L	1.28 mH
I_{PV}	5.32A	C	1.31μF
V_{PV}	37.6V	$V_{in} = V_{PV}$	112.8V
I_{sc}	5.60A	α	0.718
V_{oc}	46.0V	V_{dc}	400 V

Considering the intensity of irradiance then

$$I_{S(G)} = I_{S(Gn)} \frac{G}{G_n} \quad (16)$$

Gn is the normal value of irradiation Saturation current I0 is calculated at IPV = 0, then I0 at TR is given by

$$I_O = \frac{I_s}{\left(e^{\frac{V_D}{\gamma V_T}} - 1\right)} \quad (17)$$

The fundamental problem of employing renewable energy sources to generate electricity is low voltage output. To enhance the voltage level, the RES output is sent to a DC-DC boost converter. The boost converter output voltage is regulated by the duty cycle of the control switch. Hence, by adjusting the switchON time, one can alter the output voltage. The formula used to calculate the average output voltage over the duty cycle 'α' is

$$V_{dc} = V_{PV}\left(\frac{1}{1-\alpha}\right) \quad (18)$$

The value of inductor and capacitors are calculated using

$$L = \frac{V_{PV}\alpha}{(f_s * \Delta I_L)} \quad (19)$$

$$C = \frac{I_0\alpha}{(f_s * \Delta V_{dc})} \quad (20)$$

The input current and output voltage ripple factors are 1IL and 1Vdc, respectively, and the switching frequency is fs . For a realistic estimation of inductor and capacitor values, 1IL should be restricted to 30%, and 1Vdc is commonly assumed at 5%. TABLE 4 lists the features of the solar PV boost converter

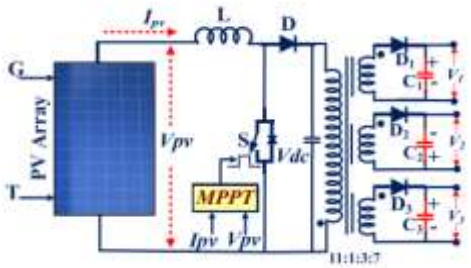

FIGURE 5. SIMO isolated DC-DC converter

Figure 5 shows a single-input multi-output (SIMO) circuit that receives the output of the DC-DC boost converter [38]. Boost converter output is fed into the primary winding of a transformer and secondary of multi winding transformer gives three output ports with tur's ratio of 11:1:3:7. At the output terminal of each DC-DC converter output port, a diode and a capacitor are connected. The diode is positioned to prevent the capacitor's reverse current from flowing into the transformer windings. The operation of the boost converter is regulated by the MPPT controller depending on inputs such as environmental parameters (solar radiation and temperature), PV array parameters (Voc and Isc), and outputs like DC link voltage. The operational performance of traditional incremental and conductance MPPT algorithms is lower if the operating point is fluctuating around the MPP and under rapidly changing irradiance conditions. To address these issues, an enhanced INC MPPT is employed [39]. The circuit diagram of the PV-fed MLI-DVR connected to the grid is shown in Figure 6.

V.OPERATION AND CONTROL OF PV-FED MLI-DV WITH FUZZY LOGIC

Depending on the type of load and voltage sag, the DVR compensating technique differs. This is because only a few loads respond to fluctuations in voltage magnitude, while others are sensitive to deviations in phase angle, and still, others

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are sensitive to both. As a result, the load characteristics dictate which control approach to employ. The pre-sag compensation (PSC) method is used to compensate for both the magnitude and phase angle of the voltage sag [40]. In this strategy load voltage is maintained with the pre-sag voltage, therefore no voltage disturbance is sensed by the load because the load voltage is having the same magnitude and phase angle, hence it is also known as the voltage quality optimized technique. The vector representation of PSC is shown in Figure. During sag, the DVR is controlled by adding more real power, which affects the rating of direct energy storage or energy received from the grid hence the requirement of energy source to supply active power will increase apart from reactive power injected by the inverter. It is acceptable for both balanced and unbalanced sensitive loads heaving phase jump or not.

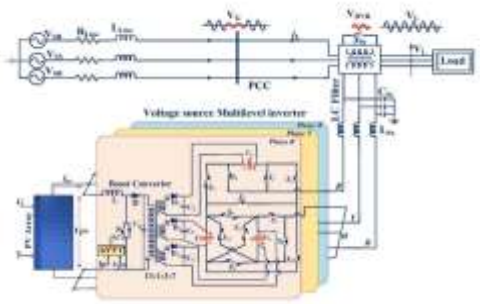

FIGURE 6. Proposed solar PV-fed MLI-DVR configuration.

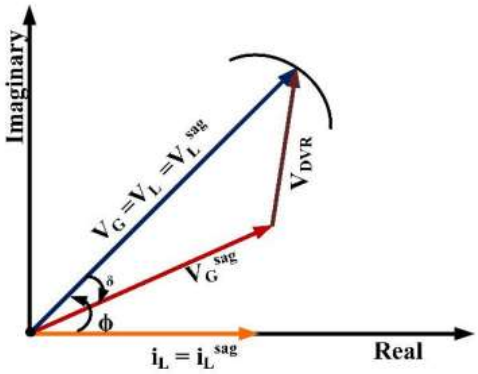

FIGURE 7. Pre sag voltage injection technique for DVR

Equation 21 gives the magnitude of VDVR and the phase angle of VDVR is obtained from equation 22.

$$V_{DVR,p} = \sqrt{2}\sqrt{(V_L)^2 + (V_G^{Sag})^2 - (2V_L V_{G,p}^{Sag}\cos(\delta_p))} \quad (21)$$

$$\angle V_{DVR,p} = \tan^{-1}\left(\frac{V_L \sin\phi - V_{G,p}^{Sag}\sin(\phi - \delta_p)}{V_L \cos\phi - V_{G,p}^{Sag}\cos(\phi - \delta_p)}\right) \quad (22)$$

where VDVR is the DVR injected voltage, 8 is the phase angle between VL and IL, V Sag G is the grid voltage at sag, δ is the corresponding angle of phase jump to V Sag G , p is the corresponding phase of the supply voltage (R, Y, or B).

VI.CONTROL SCHEME OF THE DV

A voltage disturbance duration (both start and end), phase jump, and depth depend on the type of voltage disturbance. Various methods for sensing voltage disturbances are presented in [41]. The Park transformation is utilized to transform the three-phase load voltages VL RYB and reference voltages Vref,RYB into vectorized dq0 voltage components VL,dq0, and Vref,dq0. The following formula is used to compute the three-phase reference voltage:

$$\begin{bmatrix} V_{R\,ref} \\ V_{Y\,ref} \\ V_{B\,ref} \end{bmatrix} = V_{L\,max} \begin{bmatrix} sin\omega t \\ sin\left(\omega t - 120^0\right) \\ sin\left(\omega t + 120^0\right) \end{bmatrix} \quad (23)$$

Then, using the Park transformation, it is changed from RYB to dq0 components (24), as shown at the bottom of the next page. Once the load and reference voltages change into the dq0 frame, the error signal er will be obtained in terms of magnitude and phase shift of voltage, as shown in figure 8b.

$$|e_{r\,dq0}| = \sqrt{\left(V_{dref} - V_{di}\right)^2 + \left(V_{qref} - V_{qi}\right)^2 + \left(V_{0ref} - V_{0i}\right)^2} \quad (25)$$

Fuzzy Logic Controller Design

Selection of Input and Output Variables

The key variables influencing power quality are:

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- **Voltage Error (Ve)**: The difference between the reference voltage and the actual output voltage.
- **Change in Voltage Error (ΔVe)**: The rate of change of the voltage error.

The primary output is:

- **Modulation Index (MI)**: Adjusts the amplitude of the inverter output to maintain desired voltage levels.

Fuzzification

Input variables (Ve and ΔVe) and the output variable (MI) are fuzzified into linguistic terms using membership functions. For example:

- **Ve**: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Large (PL).
- **ΔVe**: Negative (N), Zero (Z), Positive (P).
- **MI**: Decrease Large (DL), Decrease Small (DS), No Change (NC), Increase Small (IS), Increase Large (IL).

Rule Base

A set of if-then rules correlates the input conditions to an appropriate output action. For example:

- If **Ve** is **PL** and **ΔVe** is **P**, then **MI** is **IL**.
- If **Ve** is **Z** and **ΔVe** is **Z**, then **MI** is **NC**.
- If **Ve** is **NM** and **ΔVe** is **N**, then **MI** is **DS**.

Inference Mechanism

The Mamdani inference method evaluates the fuzzy rules and combines them to produce a fuzzy output set, which is then aggregated.

Defuzzification

The centroid method converts the aggregated fuzzy output set into a crisp value for the modulation index.

The change in the dq0 components will result from variations in magnitude and phase shift of voltage. Changes in the

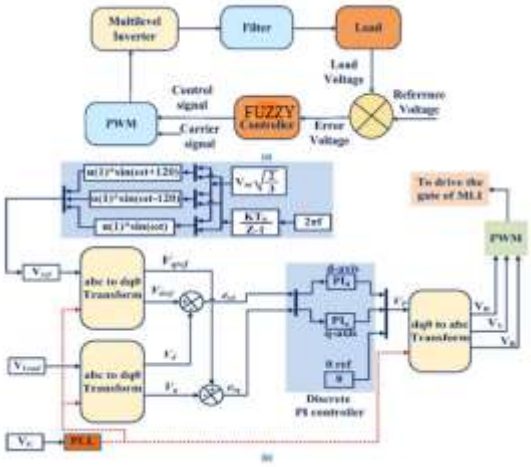

FIGURE 8. DVR WITH FUZZY controller

VII.SIMULATION RESULTS

The FLC is validated through simulation using tools like MATLAB/Simulink. The setup includes modeling the PV array, DC-DC converter, multilevel inverter, and grid interface. Various scenarios are tested to evaluate the FLC's performance in maintaining power quality under different conditions. After successful simulation, the FLC is implemented in hardware and tested with an actual PV system and multilevel inverter, monitoring the system's response to changes in solar irradiance, load variations, and grid conditions.

The proposed multilevel inverter solar PV fed DVR is evaluated in terms of improving voltage profile. The results are shown using the MATLAB/Simulink platform. Table2 lists the parameters of DVR. The DVR is connected to the system through a 10 KVA, 400V (1:1) injection transformer. The output voltage of a PV array are increased to 400V with a boost converter. To keep the DC link voltage constant, a 500Ah battery with a 400V normal voltage is used and an 8 kW, 0.85 lagging PF linear load (RL Load) is considered. The simulation results of PV and boost converter with EINC MPPT are shown in Figure. 10. PV at MPP generates

TABLE2 . DVR parameters and ratings

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Source (AC grid)	400V, 50 Hz
DC-link voltage	400V
Filter	L=5 mH, C=80 µF, R=1.5Ω
Switching frequency	5kHz
Transformer ratio	1:1

112.8 volts and by using a boost converter it is boosted to 400 volts which are appeared at the DC link. Figure 11 represents the R phase voltage waveform of an asymmetrical 23-level MLI. Voltage sag mode is created by applying overload at time intervals ranging from 0.2 sec to 0.285 sec. In this test, 0.5pu of sag is applied in comparison to load point reference voltage.

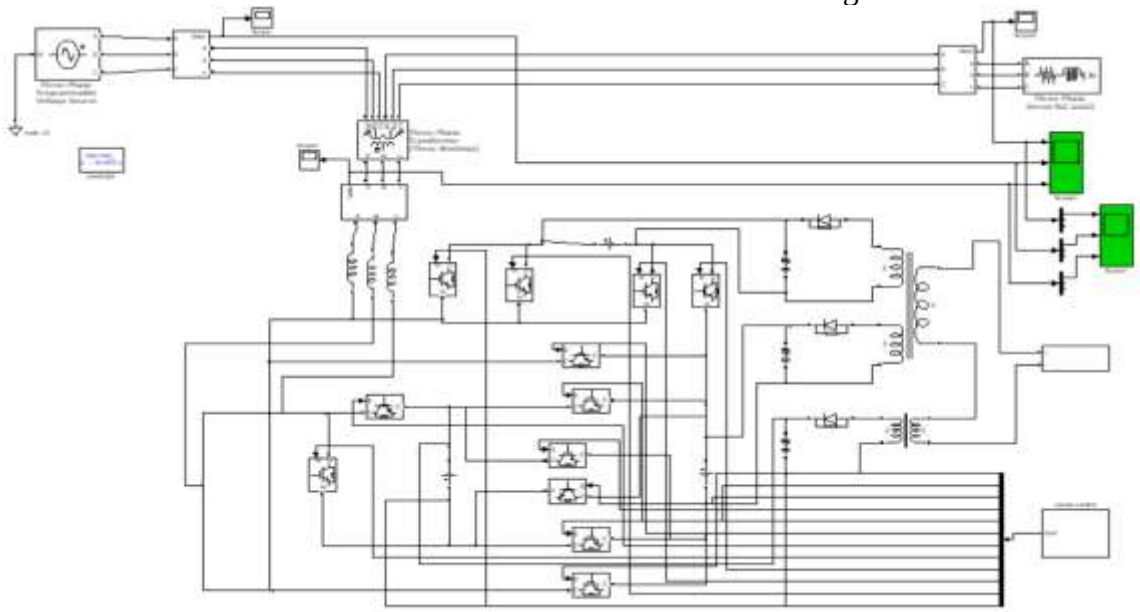

FIG9: SIMULATION DIAGRAM

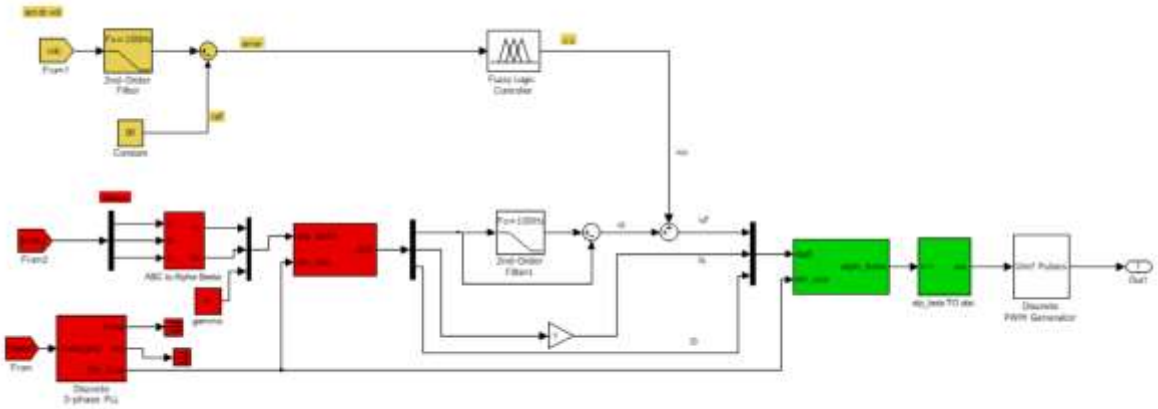

FIG10: CONTROL DIAGRAM

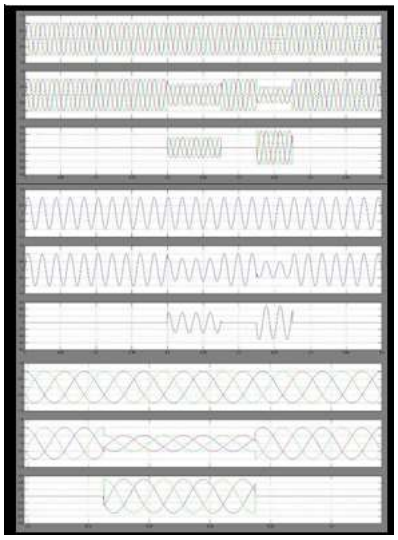

FIG11: SIMULATION WAVEFORM

VIII.CONCLUSION

PV-fed MLI-DVR using a rotating dq reference frame controller with an asymmetrical 23-level MLI is proposed in this article. A novel multilevel inverter is designed and implemented experimentally with a laboratory prototype. A synthesized output voltage of the proposed MLI is obtained with a low THD utilizing fewer circuit components. There exits various outstanding features of the proposed MLI such as the TSVPU is 2.4 whereas the cost function (CF/L) values for 'α' are 1.07 and 1.15 respectively, therefore the proposed MLI is cost-effective and superior than the existing topologies. The results of the proposed PV-fed MLI-DVR are verified with the OPAL-RT real time simulator testing platform. The proposed system efficiently minimizes the voltage sag and preserves the DC link voltage to be stable.The fuzzy logic controller for a multilevel inverter in a grid-connected solar PV system enhances power quality by reducing voltage fluctuations, harmonic distortion, and reactive power imbalances. The adaptive nature of fuzzy logic control makes it well-suited for the dynamic and nonlinear characteristics of renewable energy systems. Future work will focus on optimizing the FLC design, integrating hybrid control strategies, and validating the system in large-scale applications.

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