Comparative Analysis and Control of Cascaded H-Bridge Multilevel Inverters for Grid-Connected PV Systems Based on Sinusoidal Pulse Width Modulation

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Abstract-- Due to its flexibility and lower voltage stress between the switches, multilevel inverters are a viable option for high power applications at medium voltage. Cascaded H Bridge Multilevel Inverters (CHB-MLI) are regarded as the optimal option for grid linked Photovoltaic (PV) systems due to their need for multiple sources on the DC side. MLIs are used to provide superior output quality with less harmonic distortion compared to a two-level inverter. This article presents a comparative examination of CH-MLI's. The control technique utilizes Sinusoidal Pulse Width Modulation (SPWM) because of its simplicity in implementation. Increasing the number of levels leads to a decrease in total harmonic distortion (THD) and produces an output that is close to a sinusoidal waveform. The simulation is conducted using MATLAB/Simulink.

Keywords *— Cascaded H Bridge Multilevel Inverter (CHB- MLI), Photovoltaic (PV), THD, SPWM*

I. INTRODCUTION

In the pursuit of sustainable energy solutions, photovoltaic (PV) systems have emerged as a prominent source of renewable power [1]. However, integrating these systems with the conventional power grid requires effective conversion from DC to AC, posing technical challenges, particularly concerning harmonic performance. Addressing this issue, Cascaded H-bridge multilevel inverters have gained attention as a transformative technology [2]. These innovative inverters offer a modular architecture with multiple H-bridge modules interconnected in a cascaded fashion. This setup allows them to efficiently convert DC power generated by PV arrays into grid-compatible AC power while significantly improving harmonic performance [3]. By generating high-quality, low-distortion sinusoidal waveforms, they minimize electrical noise and distortion, ensuring the seamless integration of PV-generated electricity into the grid. This paper delves into the design, operation, and performance evaluation of Photovoltaic Connected Cascaded H-bridge multilevel inverters, emphasizing their remarkable ability to enhance harmonic performance [4]. We explore the potential of these inverters to revolutionize renewable energy integration, reduce grid disturbances, and contribute to a greener and more sustainable energy landscape. Through detailed analysis and experimental validation, we aim to highlight their practicality and advantages in real-world PV applications, ultimately paving the way for cleaner and more efficient energy generation and utilization [5].

1.1 Components of Solar PV Grid Connected Inverter System: Main components of a solar PV based grid interactive inverter system are shown in figure 1.

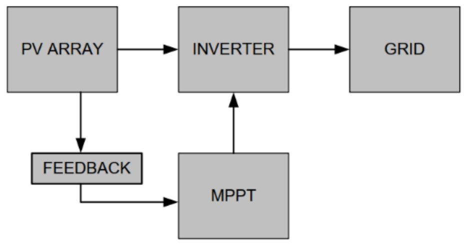

Figure 1: Components of a grid interactive inverter system

1.2 Types of Multilevel Inverters

Multilevel inverters are specialized power electronic devices used for high-voltage, high-power applications. They provide multiple voltage levels in the output waveform, reducing harmonic distortion and improving the quality of the generated AC power [6]. Here are some common types of multilevel inverters:

- Diode-Clamped Multilevel Inverter (Neutral-Point Clamped Inverter): This type of multilevel inverter uses diodes and capacitors to create multiple voltage levels [7]. It has a fixed DC bus voltage and can generate several different output voltage levels, making it suitable for medium-voltage applications.
- Flying Capacitor Multilevel Inverter (Capacitor-Clamped Inverter): Flying capacitor inverters use multiple capacitors to achieve voltage steps [8]. The capacitors are switched to various voltage levels to create the desired output waveform. They are commonly used in medium-voltage drives and renewable energy systems.
- Cascaded H-Bridge Multilevel Inverter: Cascaded H-bridge inverters consist of multiple H-bridge modules connected in series [9]. Each H-bridge module can independently control its DC source,

allowing for precise voltage level generation. These inverters are highly modular and scalable, making them suitable for a wide range of applications, including high-voltage transmission and renewable energy systems.

- Hybrid Multilevel Inverter: Hybrid multilevel inverters combine different multilevel techniques, such as diode-clamped and cascaded H-bridge configurations, to optimize performance and reduce component count. They aim to strike a balance between efficiency and complexity [10].
- H-bridge Multilevel Inverter: This is a simpler form of multilevel inverter that uses H-bridge modules to create multiple voltage levels. While not as complex as some other multilevel inverters, it is still effective in reducing harmonic distortion and improving power quality. It is often used in low to medium-voltage applications [11].
- T-type Multilevel Inverter: T-type inverters utilize a combination of switches and capacitors to achieve multilevel output voltage levels. They are known for their ability to reduce common-mode voltage and electromagnetic interference in motor drives and other high-power applications [12].
- Neutral Point Clamped (NPC) Multilevel Inverter: NPC inverters are a variation of the diode-clamped inverter that provides better voltage balance among the phases. They are commonly used in medium-voltage motor drives and industrial applications.

The choice of multilevel inverter type depends on the specific application, voltage requirements, and desired performance characteristics. Each type offers advantages and trade-offs, making it important to select the most suitable one for a particular application.

II. METHODOLOGY

2.1 Solar (PV) Systems

The solar PV system includes a PV module, dc/dc boost converter, maximum power point tracking algorithm, and load. PV modules receive radiation (R). It creates V and I for the load [13]. A photovoltaic (PV) array's voltage power characteristic is nonlinear and time-varying according to atmospheric conditions. PV module output power varies with solar radiation and temperature. The PV module must run at its maximum PV characteristic to maximize efficiency. The highest power point depends on non-direct temperature and irradiation. The best power point following control framework is used and works on non-straight parameters like temperature and radiation [14]. A MPPT maximizes solar PV module power and transfers it to the load. DC/DC converters (boost converters) transmit maximum solar PV module power to the load. A dc/dc converter connects load and module. Figure 2 shows the DC/DC converter with maximum power point tracking method and load. Changing the duty cycle changes the source's load impedance and matches it at peak power to transmit the most power. MPPT methods are required to keep PV arrays at MPP [15].

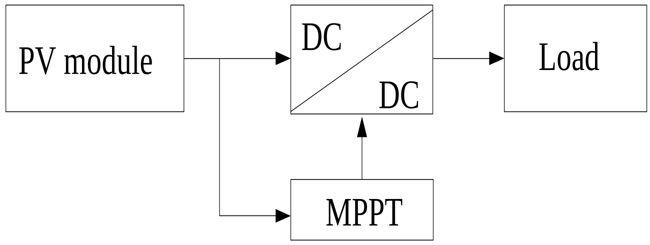

Figure 2: Block Diagram of PV System with MPPT

2.2. Maximum Power Point Tracking

MPPT aids PV applications. Solar radiation and temperature are the main factors affecting photovoltaic power. PV modules provide the maximum power at the "most extreme power point" (pinnacle control voltage). MPPT's main rule is to extract the most power from the solar and send it to the pile via a dc-to-dc converter that steps up/down the voltage [16]. The load-line and current-voltage curve meet at a PV generator's operational point. This operating point may be far from the generator's MPP, squandering much solar power. A simple dc-dc converter is used as an MPP tracker to match the PV generator and load. MPPT algorithms increase load power by controlling converter duty ratio. Many MPPT algorithms have been suggested [17], including P&O. This basic technique is straightforward to develop and does not need PV generator parameters or sun intensity and cell temperature measurements. The method perturbs the operational point by slightly changing a control parameter and estimates PV array output power before and after. If power rises, the algorithm perturbs the system in the same way; otherwise, it perturbs in the opposite direction (Figure 3).

Reference voltage perturbation and direct duty ratio perturbation are typical P&O algorithm implementation methods. PV array output voltage reference is utilized as a control parameter with a controller (typically a PI controller) to adjust MPPT power converter duty ratio for reference voltage perturbation [18]. The system is operated at the MPP voltage standard test condition (STC) to adjust the PI controller gains. The MPPT algorithm controls the reference voltage while maintaining these improvements. Direct duty ratio perturbation uses the MPPT converter duty ratio as the control parameter.

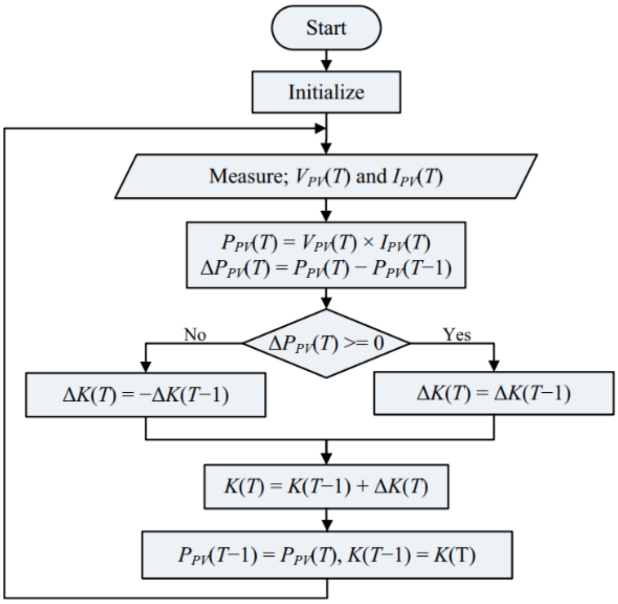

Figure 3: Flowchart of P&O MPPT algorithm

2.3 Cascaded H-Bridge Multilevel Inverter (CH-MLI)

Grid-connected PV systems' efficiency, power quality, and grid compatibility depend on inverter architecture. The Cascaded H-Bridge Multilevel Inverter (CH-MLI) is a popular option owing to its features. For grid-connected applications, CH-MLI produces high-quality, low-harmonic output waveforms. Its cascading H-bridge modules provide accurate output voltage control and modulation [19]. CH-MLI can scale to meet grid-connected system voltage and power ratings due to its versatility. CH-MLI generates various voltage levels, minimizing output Total Harmonic Distortion (THD) and ensuring power quality. Its step-like voltage levels reduce switching losses, improving efficiency. CH-MLI emits less electromagnetic interference, minimizing the danger of grid-connected sensitive electronics malfunctioning. The topology's ability to synchronize with grid frequency and voltage makes it suitable for grid applications [20]. CH-MLI helps manage grid voltage variations and disturbances. It can readily adjust to grid operating needs and PV system output. Maintenance and repair are easier with modularity since an H-bridge module may be changed without disrupting the system. CH-MLI's robust design ensures grid-connected PV system reliability and avoids system failures and downtime. High-voltage handling makes it suited for medium to high-power grid applications, including commercial and industrial [21]. CH-MLI's innovative control algorithms improve power conversion and grid integration. It is ideal for delicate loads because to its excellent power quality. CH-MLI's versatility allows incorporation of renewable energy sources beyond PV systems [22]. The topology meets regulatory criteria by meeting industry and grid code performance standards. CH-MLI's selection highlights its success in grid-connected applications that need high efficiency, power quality, and dependability. It will improve grid stability and ease the transition to a renewable energy future [23].

2.4 Phase Shifted (PS-PWM)

PSPWM is a logical extension of PWM that was designed for FC and CHB converters. Each FC cell is a two-level converter and each CHB cell is a three-level inverter, therefore bipolar and unipolar PWM may be employed. These topologies are modular, thus each cell may be modified individually using the same reference signal [24]. A phase shift between adjacent cell carrier signals creates a phase-shifted switching pattern. This creates a stepped multilayer waveform when joined. In a CHB Inverter, 180 or 360°/k carrier phase changes result in the lowest distortion. (where k=power cells). Because FC and CHB cells create two and three levels, respectively [25], this discrepancy exists.

All cells are regulated with the same reference and carrier frequency, thus switch device use and average cell power are uniformly distributed. Multipulse diode rectifiers help minimize input current harmonics for the CHB. In the FC, the even power distribution has the advantage that once the flying capacitors are properly charged (initialized to their values), the topology self-balances, so the dc-link voltages do not need to be controlled [26]. The total output voltage switches k times the frequency of each cell's switching pattern, which is intriguing. Carrier phase-shifts cause this multiplicative effect.

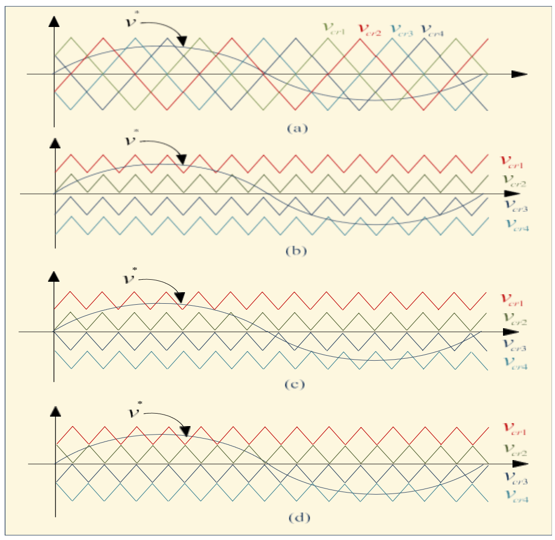

Figure 4: Phase shifted and Level shifted PWM carrier arrangements

(a) Phase shifted PWM (b) PD, (c) POD, (d) APOD

Hence, better total harmonic distortion (THD) is obtained at the output, using k times lower frequency carriers.

2.5 Level Shifted PWM (LS-PWM)

Level-shifted PWM (LSPWM) is multilevel inverters' natural extension of bipolar PWM. Bipolar PWM compares one carrier signal to the reference to choose between two voltage levels, usually the VSI's positive and negative busbars [27]. Generally, a multilayer inverter requires m−1 carriers. They have vertical shifts instead of PS-PWM's phase-shift. Each carrier is adjusted between two voltage levels [28], so B level moved. Since each carrier has two levels, bipolar PWM may be used, but the control signal must be directed to the right semiconductors to create the levels. The converter's amplitude range is covered by the carriers. They can be arranged in vertical shifts, with all signals in phase, Phase disposition (PD-PWM), all positive carriers in phase and opposite the negative carriers, Phase opposition disposition (POD-PWM), and alternate phase opposition disposition (APOD-PWM), which is obtained by alternating the phase between adjacent carriers [29]. Figure 4 shows these setups for a five-level inverter with four carriers.

Phase shifted PWM provides advantages over level shifted PWM, including no switching rotation, lower switching losses, and ease of implementation. This article implements all productive topologies using sinusoidal PWM [30]. Next sections describe traditional CMI topology, performance verifications, and challenges.

III. SIMULATION RESULTS & ANALYSIS

3.1 Results

To evaluate the performance of the proposed Simulink Model – Dual Diode PV Model with Cascaded H-Bridge Multilevel PV Inverter_ Phase-shifted SPWM (PS-SPWM) switching scheme is then applied to control the switching devices of each H-bridge. and the control system, MATLAB/Simulink software has been utilized. Table 1 shows the characteristics of the simulated system.

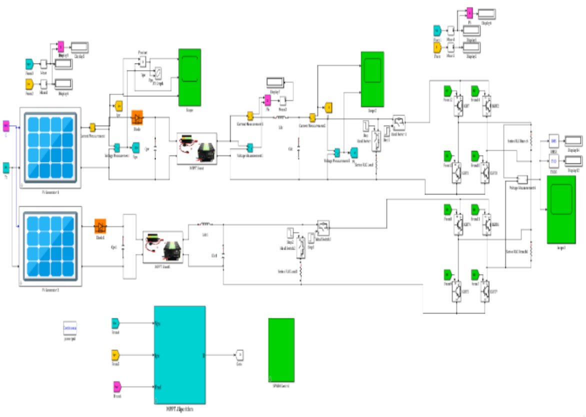

Figure 5: MPPT Algorithms & Cascaded H-bridge Multi Level Inverter

TABLE 1: PV PARAMETERS

PV Paramters

Parameter	Value	Parameter	Value
Pmax (W)	200	n	1.3417
Isc (A)	8.21	Rs (ohm)	0.2172
Voc (V)	32.9	Rsh (ohm)	951.9317 (951.93)
ki (%/°)	3.18e-3/8.21 (0.00038733)	Ns	3
kv (%/°)	-0.123/32.9 (-0.0037386)	Np	3
Ncs	54		

Figure 6 shows Experimental power extracted from PV panels with MPPT_ The harvested solar power waveform of each phase with MPPT Booster Algorithms

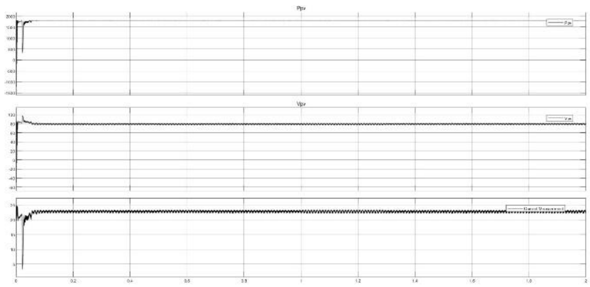

Figure 6: PV Voltage, PV Current & PV Power Vs Time in (S)

Figures. 7, 8, and 9 show the experimental output of voltage and current measurement for a dual diode, a dual generator, and a cascaded H-Bridge Multilevel inverter.

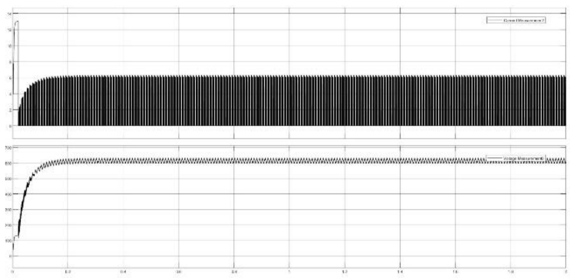

Figure 7: Voltage & Current Vs Time in (S)

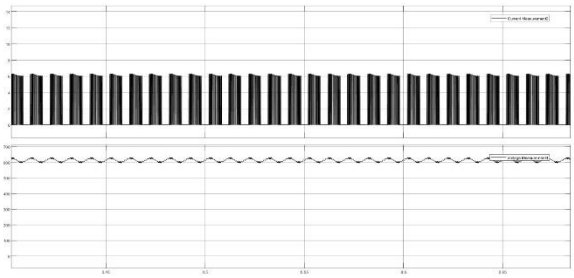

Figure 8: Voltage & Current Vs Time in (S)

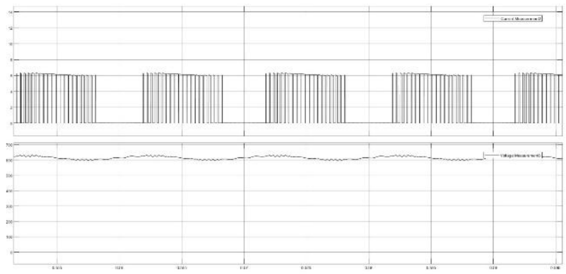

Figure 9: Voltage & Current Vs Time in (S)

Figures. 10 & 11 Shows Experimental inverter output voltages with modulation compensation _Cascaded H Bridge Multilevel Inverter Output Voltage Wave form.

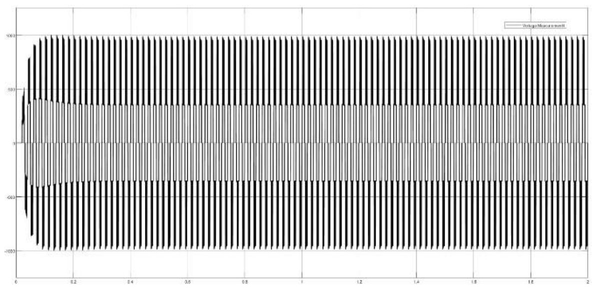

Figure 10: PV Voltage, PV Current & PV Power Vs Time in (S)

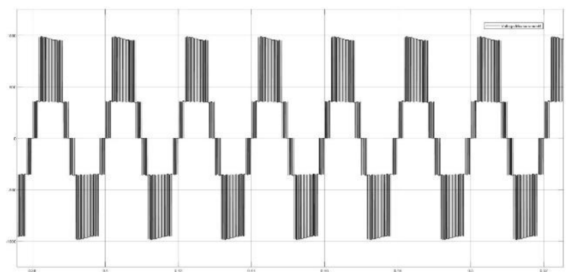

Figure 11: PV Voltage, PV Current & PV Power Vs Time in (S)

CONCLUSION

Dual Diode Photovoltaic Model Cascaded H-Bridge Multilevel PV Inverter with MPPT Booster Algorithms for Grid-Connected Applications presented in this work show that cascading H-bridge multilevel inverters are the most suitable inverter topologies for grid-connected applications. CH-MLI are performed, and a phase-shifted SPWM (PS-SPWM) switching scheme is then applied to control the switching devices of each H-bridge. The control scheme allows for high PV module utilisation and improves the overall efficiency of the PV system. The distorted grid current caused by PV mismatches is solved by modulation compensation without increasing the difficulty of the control system or causing extra power loss. Even though the capacity for balancing grid current is limited, the compensation scheme helps reduce the percentage of unbalanced grid current. And it also helps to avoid overmodulation. Hence, the findings indicate that the CHMLI produces the lowest THD contents and utilises fewer components. Moreover, the PS-SPWM produces less THD than SPWM.

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