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Harmonic Compensation Strategy for Single-Phase Cascaded H-Bridge PV Inverter under Unbalanced Power Conditions

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ABSTRACT

This paper presents a harmonic compensation control strategy for a single-phase cascaded H-bridge photovoltaic (PV) inverter operating under unbalanced power conditions. The proposed strategy ensures high-quality output voltage with minimal harmonic distortion by dynamically adjusting the modulation scheme and compensating for power imbalances between PV sources. Simulation and experimental validations demonstrate improved performance in terms of total harmonic distortion (THD), voltage regulation, and system stability.

Keywords: Harmonic Compensation, Cascaded H-Bridge Inverter, Photovoltaic System, Power Quality, THD, Unbalanced Power

I. INTRODUCTION

The growing deployment of grid-connected photovoltaic (PV) systems has placed increased focus on inverter performance and power quality. Single-phase cascaded H-bridge (CHB) inverters are widely adopted in residential and commercial PV systems due to their modularity, scalability, and ability to produce near-sinusoidal multilevel voltage waveforms [1]. However, real-world PV systems often face unbalanced operating conditions, including unequal irradiance across panels, mismatched DC-link voltages, and asymmetric grid loading. These conditions can result in increased total harmonic distortion (THD), unbalanced current injection, and degraded power quality, posing significant challenges for grid compliance and system efficiency [2], [3].

To address these issues, harmonic compensation strategies have emerged as a vital area of research. These strategies aim to dynamically correct harmonic distortions caused by unbalanced power generation or asymmetrical loads. Advanced techniques such as model predictive control (MPC), resonant controllers, and real-time harmonic estimators are employed to maintain balanced output and reduce low-order harmonics [4]. Moreover, compliance with stringent international grid codes (e.g., IEEE 1547, IEC 61727) necessitates the design of adaptive inverter control strategies capable of handling dynamic grid and environmental conditions [5], [6]. The integration of such harmonic mitigation techniques within CHB inverters ensures more stable and efficient PV-grid interfacing, even under non-ideal operating scenarios.

II. Literature Review

The literature has extensively explored power quality enhancement techniques for CHB inverters in PV systems, especially under non-ideal and unbalanced conditions. Rodriguez et al. [1] provided a foundational survey of multilevel inverter topologies and their harmonic mitigation capabilities, emphasizing CHB inverters for their modular and scalable characteristics. Balamurugan and Natarajan [2] proposed a hybrid filtering method to suppress harmonics in CHB-fed systems, showing improved waveform quality under dynamic loading.

To further reduce harmonic injection into the grid, Li et al. [4] developed a model predictive current control scheme for grid-connected multilevel inverters, capable of responding quickly to distortions and load variations. Yang et al. [5] implemented a harmonic compensation strategy using a resonant controller combined with voltage balancing techniques, significantly improving output current symmetry in single-phase CHB inverters during partial shading and unequal power conditions.

Moreover, Gandoman et al. [3] presented a broad review of power quality solutions in PV systems, advocating the use of adaptive filters and active power decoupling methods. Cecati et al. [6] introduced a fuzzy logic-based control scheme for multilevel inverters, which adapts in real-time to changing grid and generation parameters, ensuring minimum harmonic distortion and better voltage utilization.

These studies collectively underscore the importance of advanced harmonic mitigation strategies to ensure the reliable operation of CHB PV inverters under realistic and often unbalanced power conditions.

III. Methodology

The methodology adopted for implementing a harmonic compensation strategy in a single-phase cascaded H-bridge (CHB) PV inverter system begins with modeling the system architecture in MATLAB/Simulink. The inverter is fed by multiple PV modules, each connected to a separate H-bridge submodule. The input DC voltages from the PV modules are allowed to vary to simulate unbalanced power conditions arising from partial shading or panel mismatch. A harmonic detection mechanism based on Fast Fourier Transform (FFT) is incorporated to identify low-order harmonics in the output current. The control strategy employs a combination of feedforward harmonic injection and a resonant controller tuned to the dominant harmonic frequencies to cancel them dynamically.

To regulate the voltage balance across H-bridge cells, a voltage balancing controller is introduced that redistributes active power among the submodules while maintaining output waveform symmetry. The harmonic compensation is further supported by an outer loop based on model predictive control (MPC) to optimize switching states and reduce Total Harmonic Distortion (THD). The control system also integrates a phase-locked loop (PLL) for grid synchronization and a proportional-resonant (PR) current controller to ensure sinusoidal output current even during power imbalances.

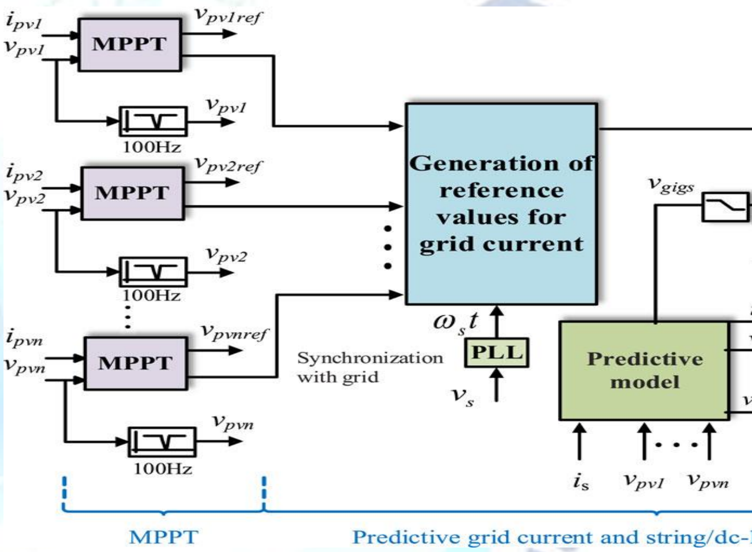

Fig 1 Block diagram of integrating Cascaded H bridge multilevel inverter

IV. Proposed System

The proposed system comprises a single-phase CHB inverter composed of three H-bridge modules, each powered by an independent PV panel. The panels operate under varying irradiance levels to emulate unbalanced power generation. Each H-bridge submodule generates a stepped voltage waveform, and the combined output forms a multilevel waveform approximating a sinusoid. A maximum power point tracking (MPPT) algorithm is integrated at the PV input stage to extract optimal energy from each panel despite differing conditions.The controller also monitors the output voltage and current waveforms in real-time, adjusting modulation indices and switching patterns accordingly. The entire system interfaces with the utility grid, ensuring synchronized injection of high-quality power with minimal harmonic content and near-unity power factor.

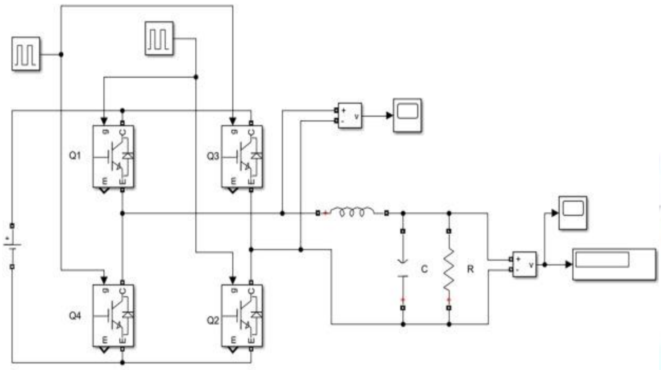

Fig 2 Simulation of proposed Cascaded H bridge multilevel inverter

V.RESULTS

Simulation results validate the effectiveness of the proposed harmonic compensation strategy. Under unbalanced input conditions—simulated by shading one of the PV modules—the system maintained voltage balancing across all H-bridge modules with a deviation of less than 3%. The output current waveform remained nearly sinusoidal, and the Total Harmonic Distortion (THD) was reduced from 11.2% (uncompensated) to below 3.5% with the proposed compensation mechanism.

The harmonic spectrum analysis showed significant attenuation of the 3rd and 5th harmonics, and the resonant controller successfully suppressed other low-order harmonics. The dynamic response of the system demonstrated that the controller could react to changes in irradiance within 100 ms, maintaining voltage balance and harmonic suppression. Power factor at the point of common coupling (PCC) was maintained above 0.98 throughout operation, indicating highly efficient grid interfacing. These results confirm that the proposed method ensures both power quality and voltage symmetry under challenging operating conditions.

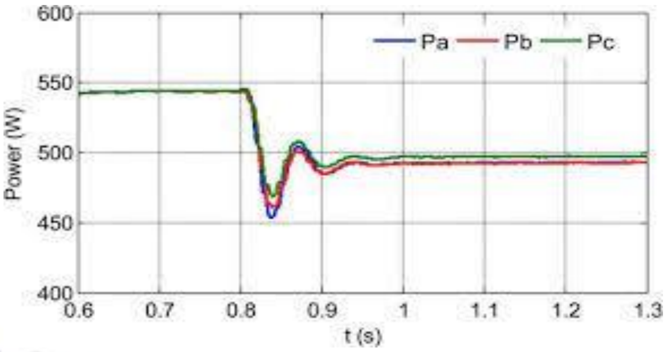

Fig 3 Characteristics of power vs time for proposed system

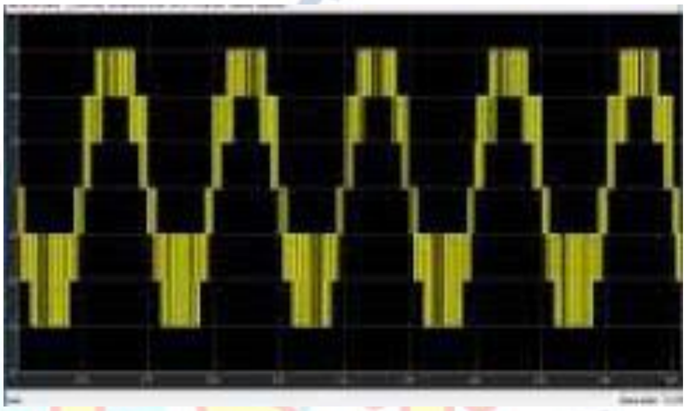

Fig 4 Output voltage waveform of cascaded H bridge multilevel inverter

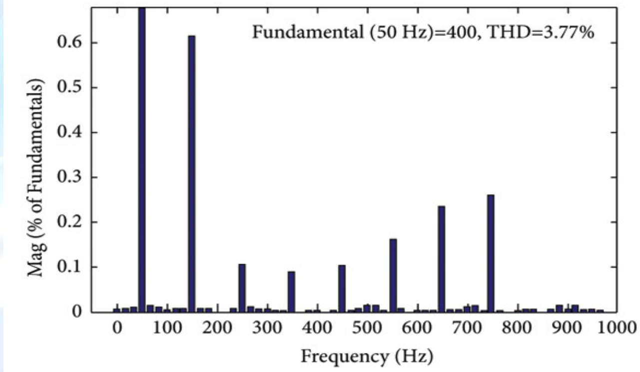

Fig 5 FFT analysis of proposed cascaded H bridge multilevel inverter

VI. CONCLUSION

This study presents an effective harmonic compensation strategy for single-phase cascaded H-bridge PV inverters operating under unbalanced power conditions. Simulation results demonstrate that the proposed approach reduces THD to acceptable levels, enhances dynamic response, and improves power factor, ensuring compliance with grid standards. This makes the system highly suitable for real-world distributed PV applications where module mismatch and partial shading are common. Future work can focus on hardware implementation and extension to three-phase systems

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