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(REVIEW ARTICLE)

Inverter topology with unipolar modulation of single-phase transformerless inverter topologies for grid-connected photovoltaic applications

Md. Aftab Alam *

Blackboard E-Learning Pvt. Ltd, Electronics and Communication Engineering, Noida, UP, India.

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Abstract

During the last decade, extensive advancements have been achieved in the research and technological development of grid-integrated photovoltaic (PV) systems. Among the essential components of such systems, the grid-connected inverter serves as the key interface that enables effective power transfer from renewable energy resources to the utility network. The rapid expansion of the solar energy sector has particularly accelerated innovation in single-phase transformerless inverter configurations designed for grid-connected PV applications. These inverter structures have attracted considerable attention because they eliminate the need for bulky line-frequency transformers while maintaining high performance standards.

Compared to traditional transformer-isolated inverters, transformerless topologies provide significant advantages, including lighter system weight, reduced installation and production costs, compact architecture, simplified circuitry, and improved power conversion efficiency. In these systems, electrical isolation can be achieved by incorporating additional switching devices either at the DC input stage or at the AC output stage. However, inverter configurations employing isolation techniques on the AC side generally demonstrate superior efficiency, primarily due to fewer semiconductor devices in the active current path, which results in lower conduction and switching losses.

This study presents a H4 Inverter topology with unipolar modulation of single-phase transformerless inverter topologies for grid-connected photovoltaic applications.

Keywords: Unipolar Modulation; PV System; Leakage Current 2; Transformerless Inverter; Common mode voltage

1. Introduction

Energy is the backbone of national development, supporting industrial growth, infrastructure expansion, and improvements in living standards. However, the continuous rise in global energy consumption, combined with the gradual depletion of fossil fuel reserves and the limitations associated with nuclear resources, has created serious challenges for sustainable power generation. Although fossil fuels remain a dominant source of electricity production, their combustion releases harmful pollutants, including greenhouse gases and particulate matter, which contribute to climate change, acid rain, and air quality deterioration. Nuclear power generation, while capable of delivering high energy output, involves substantial capital investment, complex operational requirements, radioactive waste management concerns, and significant safety risks. These constraints emphasize the necessity of transitioning toward cleaner and more sustainable energy alternatives.

Renewable energy technologies provide an effective solution to environmental and energy security concerns. Sources such as solar, wind, biomass, hydropower, tidal, and wave energy are naturally replenished and produce minimal

* Corresponding author: Md.Aftab Alam

environmental impact. Among these options, solar photovoltaic (PV) systems have experienced rapid global deployment due to their modular design, declining costs, and ease of integration into existing power networks.

For efficient utilization of solar energy, grid-connected PV systems are widely adopted. In such systems, transformerless inverter topologies have gained prominence because they eliminate bulky isolation transformers, resulting in reduced weight, lower manufacturing costs, compact structure, and improved conversion efficiency. Despite these advantages, the absence of galvanic isolation introduces technical challenges. Variations in common-mode (CM) voltage can generate leakage currents through the parasitic capacitance between the PV array and ground. These ground currents not only increase power losses but also compromise system safety and generate electromagnetic interference (EMI). Therefore, controlling and stabilizing the common-mode voltage is essential to minimize leakage current and ensure reliable inverter operation.

Photovoltaic installations are utilized in diverse applications ranging from standalone systems in remote locations to large-scale integration within distribution networks. Solar energy supports residential electrification, street and highway lighting, telecommunication infrastructure, battery charging stations, water pumping, and water treatment facilities. With continuous technological advancements, global solar deployment is expanding rapidly to meet increasing energy demands.

The overall performance of PV systems depends on several environmental and operational parameters, including solar irradiance, ambient temperature, weather variability, and conversion efficiency. External factors such as fluctuating climatic conditions and installation costs also influence system performance. To enhance efficiency and reliability, advanced transformerless inverter topologies are continuously being developed and evaluated.

In full-bridge (H4) transformerless PV inverters, various modulation strategies—such as unipolar, bipolar, and hybrid pulse-width modulation (PWM)—are commonly implemented. Unipolar modulation reduces switching transitions during zero-voltage states, thereby lowering core losses and improving overall efficiency. To further suppress leakage currents while maintaining high efficiency, several transformerless inverter designs employ modified unipolar PWM control schemes. Although bipolar sinusoidal PWM techniques can mitigate leakage current effects in H4 configurations, they often introduce higher switching and magnetic losses, which may reduce the overall system efficiency.

2. H4 Topology

The H4 full-bridge inverter topology, introduced in the mid-20th century, became one of the foundational configurations in modern power electronics. It marked an important milestone by employing actively controlled semiconductor switching devices for power conversion. This structure is capable of performing both DC–DC and DC–AC conversion, making it highly versatile in renewable energy applications.

The H4 configuration comprises four controlled power switches arranged in a bridge structure. In transformerless photovoltaic (PV) systems operating in full-bridge mode, modulation strategies such as unipolar, bipolar, and hybrid pulse-width modulation (PWM) are typically implemented to regulate output voltage and current.

Despite its structural simplicity and wide adoption, the H4 topology presents certain technical challenges in transformerless PV applications. In the absence of galvanic isolation, variations in common-mode (CM) voltage can generate leakage currents through the parasitic capacitance between the PV array and ground. These leakage currents not only raise safety concerns but also contribute to electromagnetic interference (EMI) and additional power losses. Effective suppression of leakage current therefore requires maintaining a stable common-mode voltage throughout the switching cycle. By minimizing CM voltage fluctuations, leakage currents can be significantly reduced, thereby improving system safety and performance.

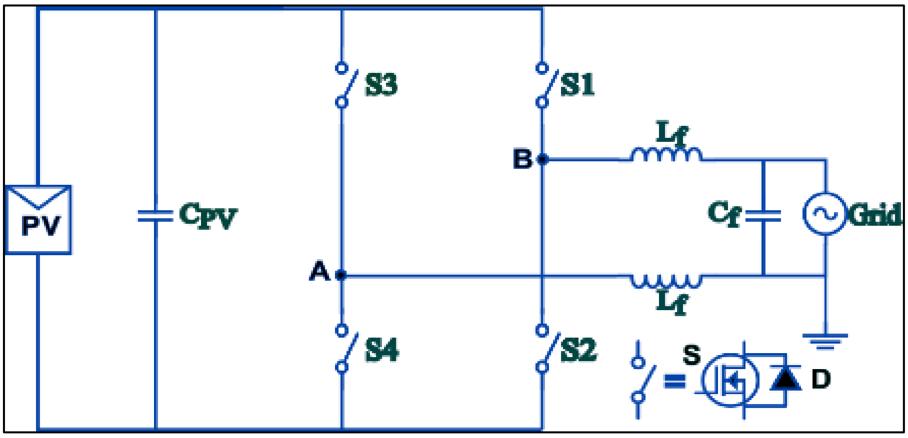

Figure 1 H4 Topology

2.1. Important Standards Dealing with PV Systems

Electricity produced by solar photovoltaic (PV) arrays and supplied to the utility grid must satisfy strict regulatory requirements established by international and national standardization bodies. In grid-connected operation, inverter performance must be evaluated against several critical technical parameters to ensure safe and reliable integration. These parameters include total harmonic distortion (THD) of the injected current, DC current injection limits, allowable grid frequency variations, power factor control capability, and leakage current levels.

For power quality compliance, the current THD delivered to the grid is generally restricted to 5% or less, thereby preventing distortion in distribution feeders and maintaining stable grid operation. In transformerless PV systems, the absence of galvanic isolation between the solar array and the utility grid introduces additional concerns. The parasitic capacitance formed between the PV modules and ground can create common-mode leakage currents, which must be carefully controlled to guarantee operational safety.

According to VDE 0126-1-1, if the leakage current exceeds 300 mA peak, the inverter is required to disconnect from the grid within 0.3 seconds. Furthermore, grid interconnection regulations such as VDE-AR-N 4105 specify reactive power support requirements, mandating that inverters operate within defined power factor ranges, including zero power factor capability when necessary for grid stabilization. Irrespective of system power rating, any leakage current exceeding prescribed safety thresholds must trigger protective disconnection within the stipulated time interval to enhance grid reliability and user safety.

Compliance with these standards ensures improved power quality, enhanced system protection, and stable operation of grid-connected photovoltaic installations.

Table 1 Various Standards and Codes for PV Systems

Standard	Parameter	Range
IEEE 1547 IEC 61727 IEC 613000-3-2	THD	<5%
VDE 01260-1-1	Leakage current	< 300 mA (peak)

2.2. H4 Topology with unipolar PWM

A bipolar H-Bridge uses diagonal switches that are switched at the same time when unipolar PWM is used, but unipolar PWM switches are not always switched simultaneously.

In this technique, sine and mirrored sine references are used as the modulating signal for each of the branches. The two references are compared to the same triangle wave to generate pulses.

2.2.1. H4 inverter switching with unipolar pulse width modulation

In unipolar modulation, during positive-half-cycles of the grid-voltage, switch S1 stays on, while switches S3 and S4 are switched at the switching frequency (fs), but switch S2 remains off. In freewheel mode, the switch for D3 and S1 is on, and the switch for S2 and S4 is off. A negative half-cycle of the grid voltage results in S3 being on, S1 and S2 being switched to the switching frequency (fs), and S4 remaining off. The D1 and S3 are on in freewheel mode, while the S2, S4 are off. Unipolar operation has the advantage of requiring less filtering and lower core loss due to the absence of zero voltage loss. Table 2, shows switching pattern. Figure 2, illustrate the control signals of H4 unipolar inverters.

Table 2 Switching state for unipolar modulation

Switches						V_{out}
S1	S2	S3	S4	D1	D3	
1	0	0	1	0	0	V_{in}
1	0	0	0	0	1	0
0	1	1	0	0	0	$-V_{in}$
0	0	1	0	1	0	0

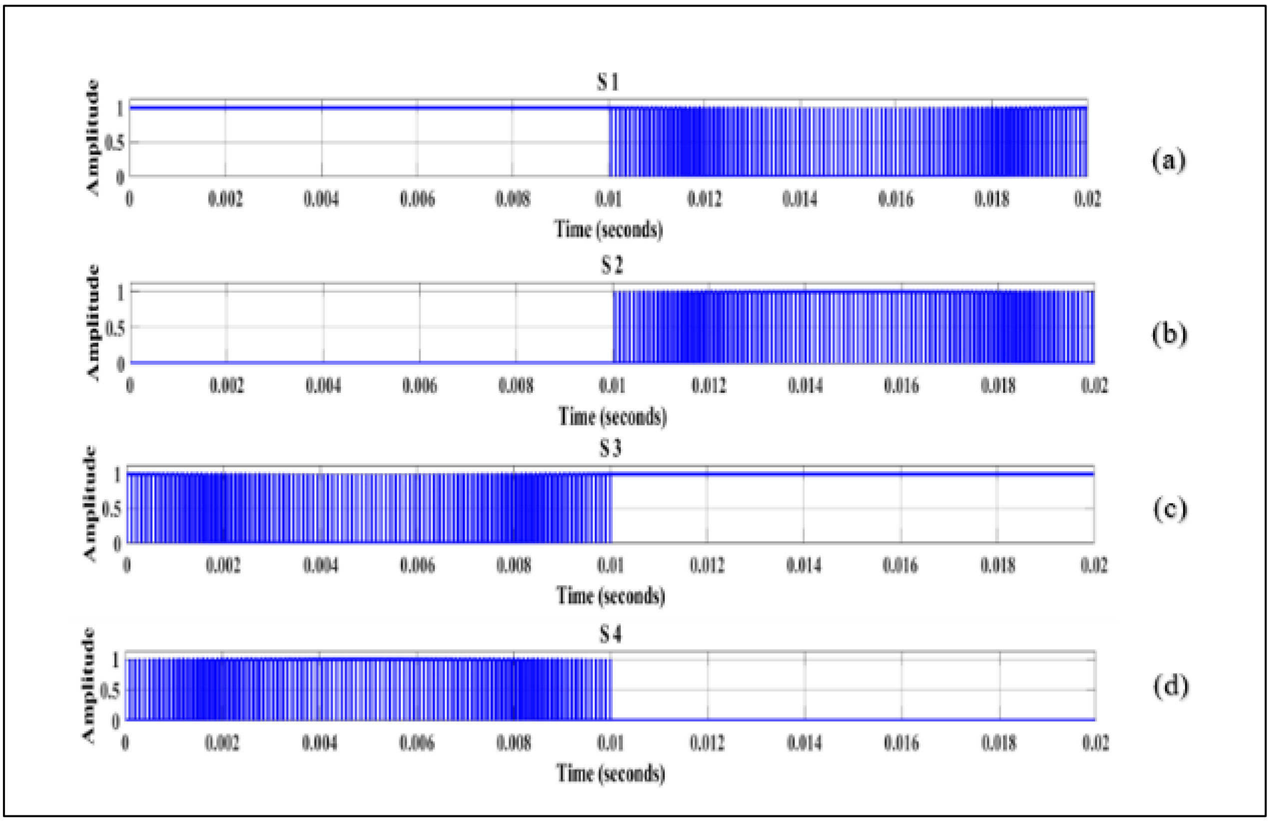

Figure 2 Control Signals (a) S1, (b) S2, (c) S3 and, (d) S4, for Unipolar Modulation

3. H4 Inverter topology operating mode with unipolar PWM

The operating modes are shown in Figures 3, 4, 5 and 6. S1 and S3 both turned on will result in zero output voltage. According to the current's direction, the current circulates through S1 & D3 or D1 & S3.

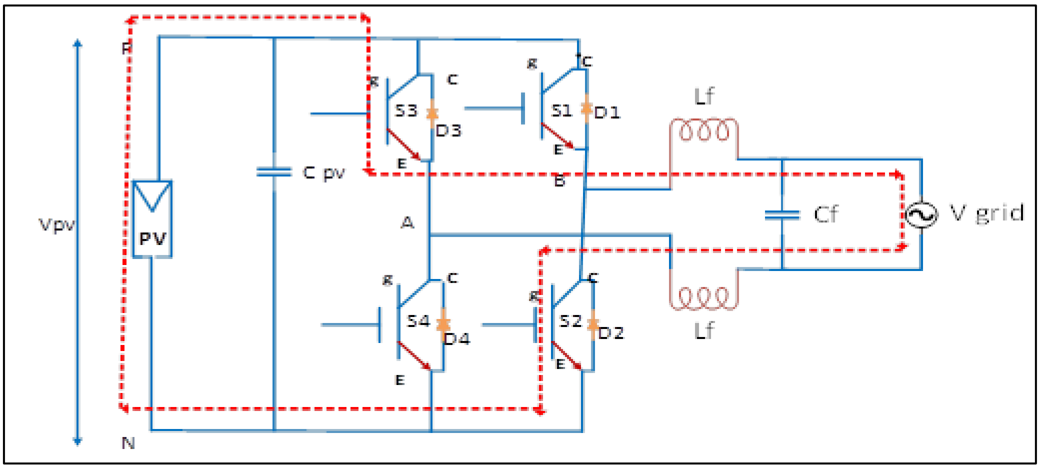

Figure 3 H4 Inverter with Unipolar PWM Modes of operation - Mode1

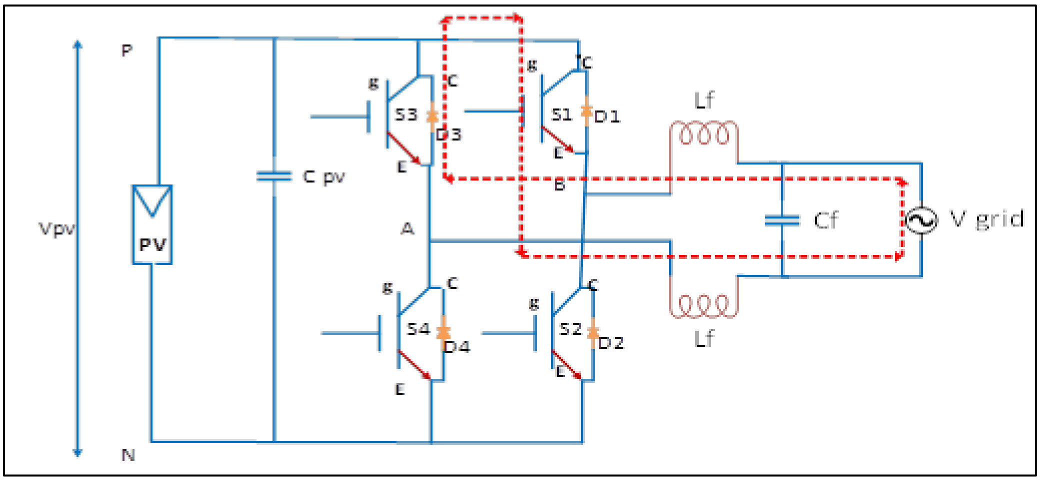

Figure 4 H4 Inverter with Unipolar PWM Modes of operation - Mode2

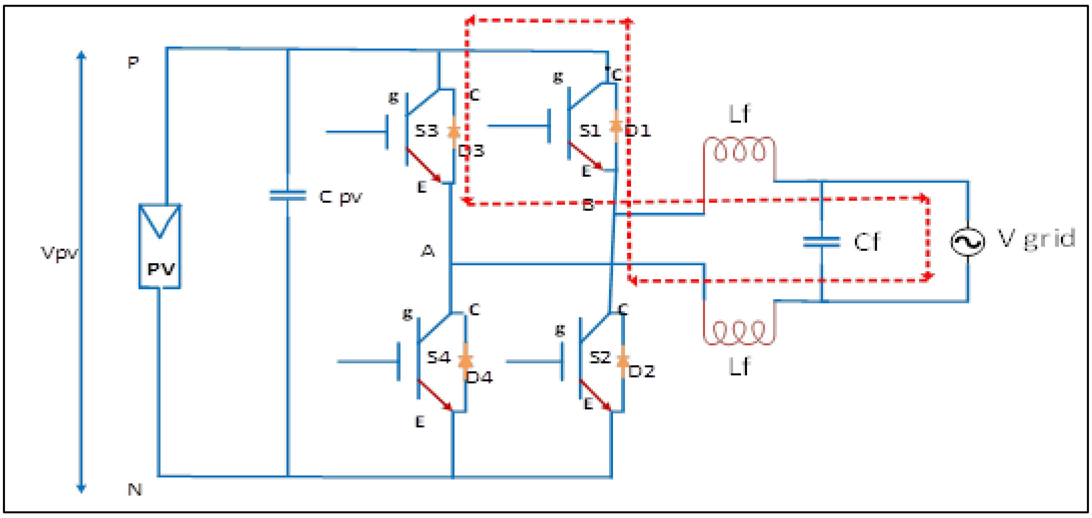

Figure 5 H4 Inverter with Unipolar PWM Modes of operation - Mode3

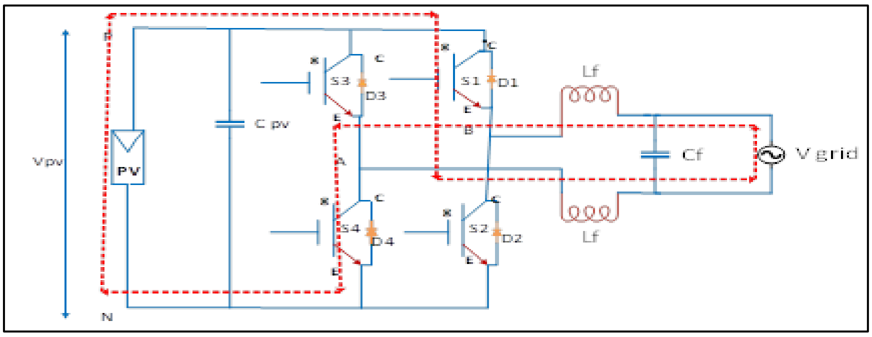

Figure 6 H4 Inverter with Unipolar PWM Modes of operation - Mode4

Output voltage varies from 0 to + and - VDC for unipolar modulation. The voltage spike is therefore reduced to VDC compared to 2 V DC in bipolar mode. Output voltages have a frequency twice that of switching voltages. In order to match the output frequency of bipolar switching, the carrier frequency must be halved.

The features of this scheme are:

- There is a lower filtering requirement for the output current since the ripple output current is twice as high as the switching frequency.
- The voltage output on the filter swings between 0 to + VDC and 0 to - VDC and therefore losses in the filter choke core are reduced.
- Higher efficiency due to relatively lower reactive power exchange between filter inductor and DC link capacitor. Because of zero output states.

4. Simulation Results and Discussion

MATLAB/Simulink has been used to simulate the H4 inverter. Each topology requires measurements of almost the same parameters, including input voltage, input current, inverter output, output voltage, THD, efficiency, and common-mode voltage and leakage current. Comparisons are made for leakage currents produced by H4 inverters with different modulation schemes.

Figure 7. Shows the Simulink model for the H4 inverters topology (with unipolar modulation). Figure 8. Shows the simulation result for the H4 inverters topology (with unipolar modulation). As shown in Table 3, all simulations are performed using the following parameters.

Table 3 Parameters for simulation

Parameter	Specification
DC-input voltage	$400V_{dc}$
V_g	1 Ph, 230 V (RMS), 50 Hz
Grid-frequency	50 Hz
Rated Power	2 kW
Switching-Frequency	10 kHz
DC-Link capacitors	2200 μF
Inductors(Filter)	3 mH
Capacitor (Filter)	6 nF
Stray capacitor	300 nF
Ground Impedance	11Ω

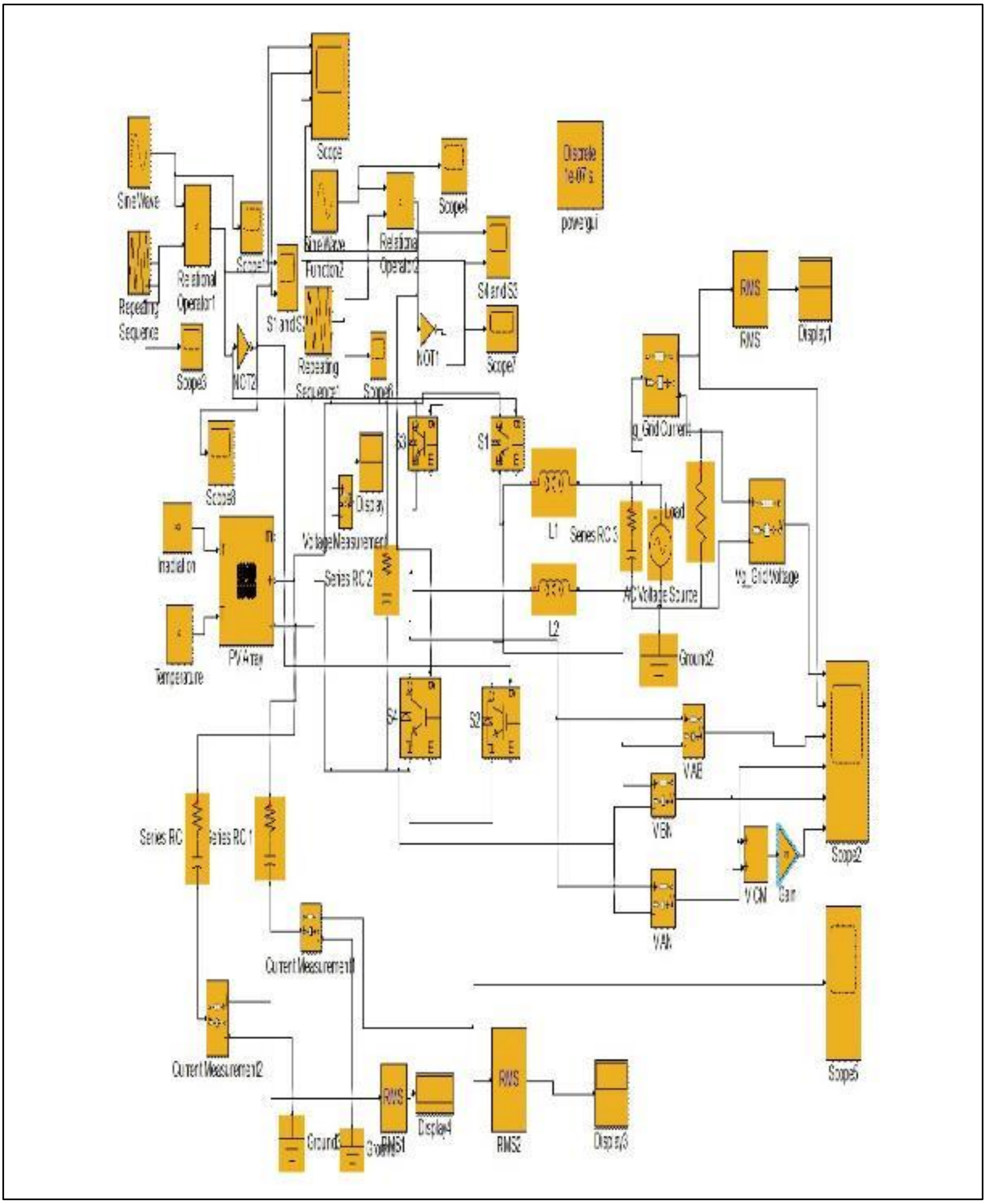

Figure 7 Simulink model for the H4 inverters topology (unipolar modulation)

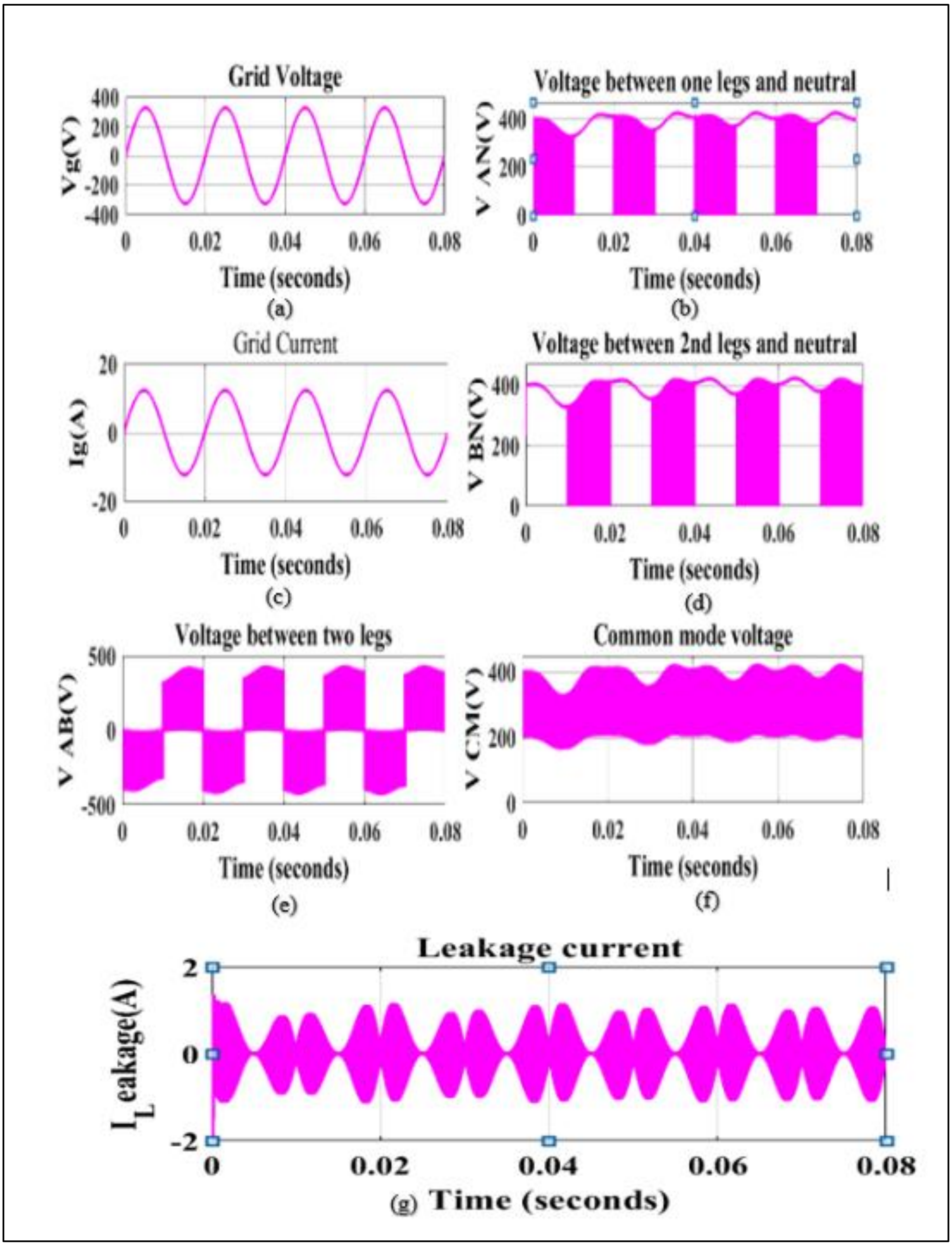

Figure 8 Waveforms of (a) V_g, (b) V_{AN}, (c) I_g, (d) V_{BN}, (e) V_{AB}, (f) V_{CM}, and (g) leakage current for H4 topology with unipolar

In the inverter H4 topology with unipolar modulation, the leakage current is 803.1 mA.

5. Conclusion

The unipolar SPWM control of full-bridge inverters is an attractive feature. However, this leads to higher leakage currents because their common mode (CM) voltage changes faster. Since unipolar modulation with H4 has limitations, the voltage swing rate of photovoltaic (PV) inverters must be reduced by developing new topologies. The advantages of unipolar modulation have made it the preferred method.

Compliance with ethical standards

Disclosure of conflict of interest

No Conflict of interest to be disclosed.

References

[1] Chamarthi, P., Rajeev, M., and Agarwal, V. (2015). A novel single stage zero leakage current transformer-less inverter for grid connected PV systems. *In 2015 IEEE 42nd photovoltaic specialist conference (PVSC)*: 1-5.

[2] Ministry of New & Renewable Energy, Government of India. Physical Progress. 2022.

[3] Verma M. Analysis, Design, and Control of a Single-Phase Single-Stage Grid-Connected Transformerless Solar Inverter. Quebec, Canada. 2019. Available from.

[4] Desai AA, Mikkili S, Senjyu T. Novel H6 Transformerless Inverter for Grid Connected Photovoltaic System to Reduce the Conduction Loss and Enhance Efficiency. *Energies*. 2022;15(10):3789.

[5] Siddiqui MI, Khan I, Ali MA. Transformerless Inverter Topologies for Grid-Connected PV System.

[6] Aljafari B, Loganathan AK, Vairavasundaram I, Ramachadran S, Nagarajan AP. Analysis of a Photovoltaic System Based on a Highly Efficient Single-Phase Transformerless Inverter. *Energies*. 2022;15(17):6145.

[7] Janardhan G, Babu NNVS, Srinivas GN. Single phase transformerless inverter for grid connected photovoltaic system with reduced leakage current. *Electrical Engineering & Electromechanics*. 2022;(5):36–40. 11) Liu Y, Zhou Y, Guo B, Wang H, Su M, Liang X, et al. Bimodal Transformerless Inverter With Three Switches. *IEEE Transactions on Industrial Electronics*.

[8] Barater, D., Buticchi, G., Lorenzani, E., and Concari, C. (2013). Active common-mode filter for ground leakage current reduction in grid-connected PV converters operating with arbitrary power factor. *IEEE Transactions on Industrial Electronics* 61(8): 3940-3950.

[9] Chaniago, K., Selvaraj, J., and Rahim, N. A. (2008). Implementation of single-phase grid connected inverter using TMS320F2812. *In 2008 3rd IEEE Conference on Industrial Electronics and Applications*: 1498-1502.

[10] Chen, B., Sun, P., Liu, C., Chen, C. L., Lai, J. S., and Yu, W. (2012). High efficiency transformerless photovoltaic inverter with wide-range power factor capability. *In 2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*: 575-582.

[11] Chen, W., Hotchkiss, E., and Bazzi, A. (2018). Reconfiguration of NPC multilevel inverters to mitigate short circuit faults using back-to-back switches. *CPSS Transactions on Power Electronics and Applications* 3(1): 46-55.

[12] Chowdhury, A. S. K., and Razzak, M. A. (2013). Single phase grid-connected photovoltaic inverter for residential application with maximum power point tracking. *In IEEE 2013 International Conference on Informatics, Electronics and Vision (ICIEV)*: 1-6.

[13] Siddiqui, A., & Asim, M. (2025). Advancement, challenges and solutions of PV integrated battery energy storage systems: A review. Journal of Energy Storage, 132, 117996.

[14] Aphiratsakun, N., Bhaganagarapu, S. R., and Techakittiroj, K. (2005). Implementation of a Single-phase Unipolar Inverter Using DSP TMS320F241. *AU JT* 8(4): 191-195.

[15] Ishtiaq, A., Siddiqui, M. A., Asim, M., & Laskar, S. H. (2023, December). Load Frequency Control for Single-Area System Using Modified PSO and Modified Grass Hopper Optimization-Based PID and PI Controllers. In International Conference on Signal, Machines, Automation, and Algorithm (pp. 687-695). Singapore: Springer Nature Singapore.

[16] Aparnathi, R. R., and Dwivedi, V. V. (2014). Design and simulation low voltage single-phase transformerless photovoltaic inverter. *Telkomnika Indonesian Journal of Electrical Engineering* 12(7): 5163-5173.

[17] Kumar Tiwari, V., Asim, M., Aftab Alam, M. D., Imran Siddiqui, M., & Alam, M. A. (2024). Implementation of Single-Phase Shift (SPS) and Extended Phase Shift (EPS) for Dual Active Bridge (DAB). Indian Journal of Science and Technology, 17(41), 4262-4269.

[18] Albalawi, H., and Zaid, S. A. (2018). An H5 transformerless inverter for grid connected PV systems with improved utilization factor and a simple maximum power point algorithm. *Energies* 11(11): 2912.

[19] Makwana, P., Asim, M., Alam, M. A., Siddiqui, A., & Bakhsh, F. I. (2024, November). Enhanced Working of Grid-linked PV with Incremental Conductance MPPT and Integrated Battery Storage. In 2024 Second International Conference Computational and Characterization Techniques in Engineering & Sciences (IC3TES) (pp. 1-6). IEEE.

[20] Cha, W. J., Kim, K. T., Cho, Y. W., Lee, S. H., and Kwon, B. H. (2015). Evaluation and analysis of transformerless photovoltaic inverter topology for efficiency improvement and reduction of leakage current. *IET Power Electronics* 8(2): 255-267.