

Multi-Objective Quantum-Inspired Adaptive SHE-PWM for Harmonic and Switching-Loss Minimisation in a Transformer-Less Single-Source Hybrid Multilevel PV Inverter

Mukesh Kumar¹, Vikash kumar²

¹ Department of Electrical Engineering Mangalayatan University Uttar Pradesh, 202146, India

² Department of Electrical Engineering Ramchandra Chandravansi University, Palamu, Jharkhand.

Abstract—Transformer-less photovoltaic (PV) inverters provide attractive advantages in terms of size, weight, cost, and conversion efficiency, but their operation is constrained by harmonic distortion, switching losses, common-mode effects, and the trade-off between waveform quality and semiconductor utilization. This paper proposes a Multi-Objective Quantum-Inspired Adaptive Selective Harmonic Elimination Pulse Width Modulation (MQI-A-SHE-PWM) strategy for a transformer-less single-source hybrid multilevel PV inverter. The proposed controller combines quantum-inspired population evolution, selective harmonic elimination, adaptive objective weighting, and switching-transition minimisation in a unified modulation framework. Instead of minimising harmonic distortion alone, the optimization simultaneously considers low-order harmonics, total harmonic distortion, fundamental-voltage tracking error, and switching activity. The switching-angle set is adaptively selected according to the inverter operating point and modulation index. A single PV dc source is used to supply the hybrid multilevel converter, avoiding the requirement for isolated dc sources and a line-frequency transformer. A simulation-oriented validation framework is established for steady-state, variable-modulation-index, and dynamic-PV operating conditions. Comparative evaluation is defined against conventional SHE-PWM and evolutionary optimization based SHE methods. The proposed framework is intended to provide a practical compromise between harmonic quality and conversion efficiency for high-performance transformer-less PV conversion systems.

Index Terms—Photovoltaic inverter, transformer-less inverter, hybrid multilevel inverter, selective harmonic elimination, SHE-PWM, quantum-inspired optimization, multi-objective optimization, switching-

loss minimisation, harmonic suppression, adaptive modulation.

I. INTRODUCTION

The increasing penetration of photovoltaic generation has intensified the need for efficient, compact, reliable, and grid-compliant power-electronic interfaces. The PV inverter directly influences the quality of injected current, conversion efficiency, electromagnetic compatibility, semiconductor stress, and system reliability. Conventional PV systems often use line-frequency transformers for galvanic isolation and voltage adaptation. Although such transformers provide isolation, they increase volume, weight, cost, and power loss. Transformer-less architectures therefore offer an attractive alternative for distributed and utility-interactive PV systems.

Removing the transformer introduces additional design requirements. The absence of galvanic isolation can increase common-mode voltage and leakage current through parasitic capacitances associated with the PV source and ground. At the same time, the inverter must maintain low harmonic distortion and high efficiency over a wide range of PV voltage, irradiance, and output-power conditions. Multilevel inverter technology provides a useful solution because several voltage levels approximate a sinusoidal waveform more closely than a conventional two-level converter. The resulting smaller voltage steps can reduce output-voltage distortion and filter requirements. Hybrid multilevel structures can further increase the number of output

levels while limiting the number of semiconductor devices and dc sources.

Modulation remains a decisive factor in determining the performance of multilevel converters. Conventional sinusoidal PWM normally requires relatively high switching frequency and can therefore increase switching loss. Space-vector methods provide good dc-bus utilisation but become computationally demanding as the number of voltage levels increases. Selective harmonic elimination PWM is attractive because it can suppress selected low-order harmonics while operating with comparatively few switching transitions per fundamental cycle.

Classical SHE-PWM obtains switching angles from nonlinear transcendental equations. Its solution can be sensitive to initial conditions, and feasible solutions may not exist over the complete modulation range. Optimization-based SHE methods alleviate some of these limitations, but many existing approaches primarily minimise harmonic distortion and do not explicitly account for switching activity or loss.

This paper proposes MQI-A-SHE-PWM to address this multi-objective problem. The main contributions are: (i) a transformer-less single-source hybrid multilevel PV inverter framework; (ii) a quantum-inspired search mechanism for switching-angle optimisation; (iii) simultaneous optimisation of harmonic distortion, switching transitions, and fundamental-voltage tracking; (iv) adaptive weighting based on operating conditions; and (v) a reproducible simulation framework for comparative evaluation.

A. LITERATURE REVIEW AND RESEARCH GAP

Multilevel inverter research has established the ability of diode-clamped, flying-capacitor, cascaded, and hybrid structures to improve voltage waveform quality and reduce semiconductor voltage stress. Foundational surveys also identify multilevel SHE-PWM and space-vector modulation as important control families for high-power conversion. [1], [2]

Optimization-based SHE methods were subsequently introduced to overcome the sensitivity of Newton–Raphson-type approaches to initial conditions and multiple feasible roots. Genetic-algorithm and particle-swarm approaches have demonstrated that switching angles can be obtained by treating SHE as a nonlinear optimization problem. [3]–[6]

PV-oriented studies have extended SHE optimization to cascaded H-bridge and renewable-energy converters. These works demonstrate the relevance of optimized switching angles under PV operation and variable modulation conditions. More recent work has also considered varying dc-source conditions and data-driven prediction of optimal firing angles, showing that fixed angle sets can become inadequate when converter operating conditions change. [7]–[10] The research gap addressed in this paper is the simultaneous treatment of harmonic quality and switching activity in a transformer-less single-source hybrid multilevel PV converter. Existing SHE optimization studies commonly emphasize harmonic elimination, whereas the proposed framework introduces a unified multi-objective cost function, adaptive weighting, and quantum-inspired population evolution. The intended contribution is therefore not a new harmonic equation alone, but an operating-condition-aware optimisation architecture that explicitly manages the quality–efficiency trade-off.

II. PROPOSED TRANSFORMER-LESS SINGLE-SOURCE HYBRID MULTILEVEL PV INVERTER

A. System Configuration

The proposed conversion system consists of a PV array, dc-link capacitor, single-source hybrid multilevel inverter, output L/LCL filter, and grid interface. The basic energy path is PV array → dc link → hybrid multilevel inverter → filter → grid. No line-frequency transformer is placed between the inverter and grid. The architecture is intended to reduce conversion-stage losses and system size while retaining the voltage-quality benefits of multilevel operation.

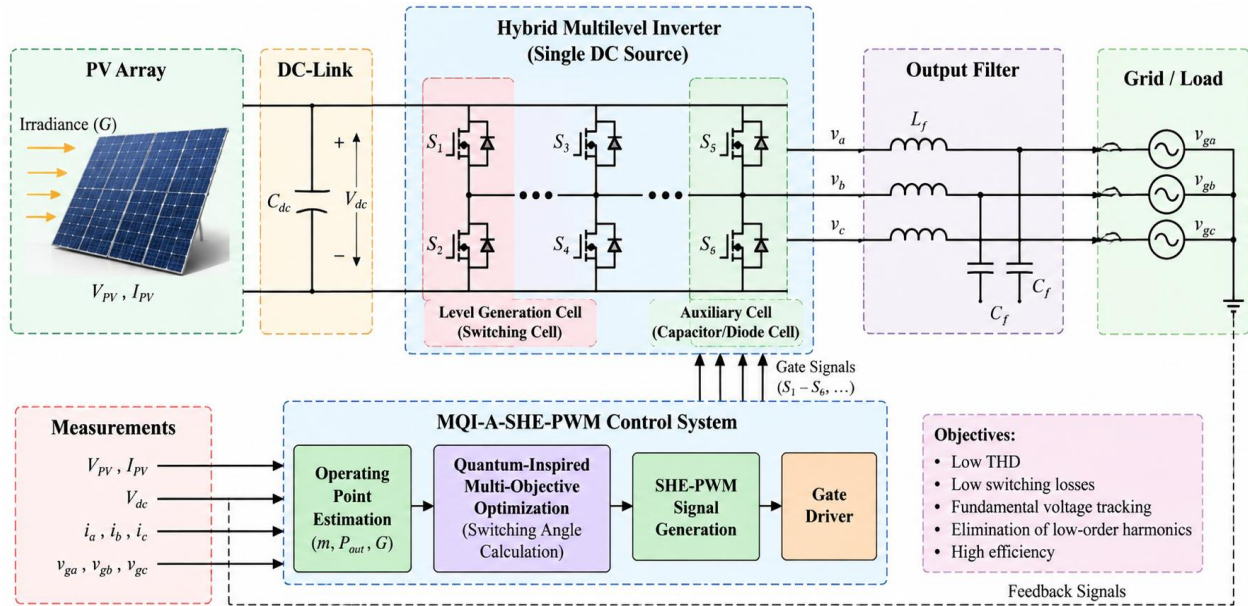


Fig. 1. Proposed transformer-less single-source hybrid multilevel PV inverter configuration.

B. Hybrid Multilevel Voltage Generation

The inverter synthesises positive, zero, and negative voltage states from the available dc-link voltage by combining switching-cell voltage contributions. For a converter containing N_s controllable cells, the instantaneous output voltage may be represented by $v_{inv}(t) = \sum_{k=1}^{N_s} S_k(t) V_k$ where $S_k(t)$ is the switching function of cell k and V_k is its voltage contribution. The topology is selected so that a relatively high number of voltage levels can be produced from a single dc source. This reduces the voltage step between adjacent states and improves the quality of the staircase waveform.

III. SELECTIVE HARMONIC ELIMINATION PWM

A. Fourier Representation

For a quarter-wave-symmetric waveform containing m switching angles in the first quadrant, the angles satisfy

$$0 < \theta_1 < \theta_2 < \dots < \theta_m < \pi/2.$$

For odd harmonic order n , the Fourier coefficient can be expressed as

$$V_n = (4V_{dc}/n\pi) \sum_{k=1}^m \cos(n\theta_k).$$

The fundamental component is therefore

$$V_1 = (4V_{dc}/\pi) \sum_{k=1}^m \cos(\theta_k).$$

The desired fundamental component is retained while selected low-order harmonics, typically the 5th, 7th, 11th, and 13th components, are strongly attenuated. The number of independently controlled harmonics depends on the number of available switching angles.

B. Limitations of Conventional SHE

The nonlinear SHE equations may have multiple roots, isolated feasible regions, or no feasible solution for a particular modulation index. Moreover, a switching-angle solution that minimises harmonic distortion may require an unnecessarily large number of transitions. This motivates a formulation in which waveform quality and switching efficiency are optimised together.

IV. PROPOSED MULTI-OBJECTIVE QUANTUM-INSPIRED OPTIMIZATION

A. Quantum-Inspired Representation

The proposed optimiser represents candidate solutions through probability amplitudes. A generic quantum state is written as

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \quad |\alpha|^2 + |\beta|^2 = 1.$$

The amplitudes define a probability distribution from which candidate switching-angle combinations are measured. This representation maintains search

diversity and permits gradual movement toward promising regions of the solution space.

B. Switching-Angle Encoding

$$\theta^* = [\theta 1^*, \theta 2^*, \dots, \theta m^*].$$

Candidate angles are generated within the quarter-wave interval and subsequently sorted and repaired so that the physical ordering constraint is always satisfied. A minimum angular separation may also be imposed to avoid excessively narrow pulses.

V. MULTI-OBJECTIVE FITNESS FUNCTION

The proposed controller does not treat THD as the sole performance metric. The overall cost function is defined as

$$J = w_H J_H + w_S J_S + w_V J_V + w_T J_T$$

where J_H is the low-order harmonic cost, J_S is the switching-activity cost, J_V is the fundamental-voltage tracking cost, and J_T is a switching-transition distribution cost. The weights are nonnegative and satisfy

$$w_H + w_S + w_V + w_T = 1.$$

A. Harmonic Cost

$$J_H = \sum_{h \in H} \lambda_h (|V_h|/V_I)^2.$$

The set H contains the targeted low-order harmonics and λ_h determines their relative importance.

B. THD Cost

$$THD = [\sqrt{\sum_{h=2 \rightarrow hmax} V_h^2} / V_I] \times 100.$$

The calculated THD is used as a principal waveform-quality indicator. Harmonic components should be extracted using the same FFT settings for every compared method.

C. Switching Activity Cost

$$N_{sw} = \sum_{k=1 \rightarrow Ns} N_{trans,k}.$$

$$J_S = N_{sw} / N_{sw,max}.$$

This term penalizes unnecessary semiconductor transitions and therefore provides a direct mechanism for reducing switching-loss-related activity.

D. Fundamental-Voltage Tracking

$$J_V = |(V_I - V_I^*) / V_I^*|.$$

This constraint prevents the optimizer from sacrificing the fundamental component merely to reduce selected harmonics.

VI. ADAPTIVE OBJECTIVE WEIGHTING

Fixed objective weights are not necessarily suitable for all PV operating conditions. At high output power, switching loss can become a significant contributor to total converter loss, whereas at lower power the optimisation can place greater emphasis on waveform quality. The proposed method therefore modifies the weights using normalized operating variables.

$$\mu_P = P/P_{rated}, \quad \mu_V = V_{dc}/V_{dc,rated}.$$

The adaptive weights are generated as functions of operating power and dc-link voltage, with normalization enforced after every update. The resulting mechanism permits a smooth transition between harmonic-quality-oriented and efficiency-oriented operation without changing the inverter hardware.

VII. MQI-A-SHE-PWM ALGORITHM

The complete optimization sequence is as follows:

Initialize the quantum-inspired population and algorithm parameters.

Measure PV voltage, PV current, dc-link voltage, and inverter power.

Generate candidate switching-angle vectors from the probability amplitudes.

Repair and sort the angles to satisfy feasibility and minimum-separation constraints.

Calculate the fundamental component and targeted harmonic magnitudes using Fourier analysis.

Evaluate THD, switching transitions, fundamental-voltage error, and transition-distribution cost.

Update the multi-objective fitness value using adaptive weights.

Update the quantum probability amplitudes toward high-quality candidate states while preserving population diversity.

Repeat the measurement, evaluation, and update stages until the stopping criterion is satisfied.

Store or output the optimal switching-angle vector for gate-pulse generation.

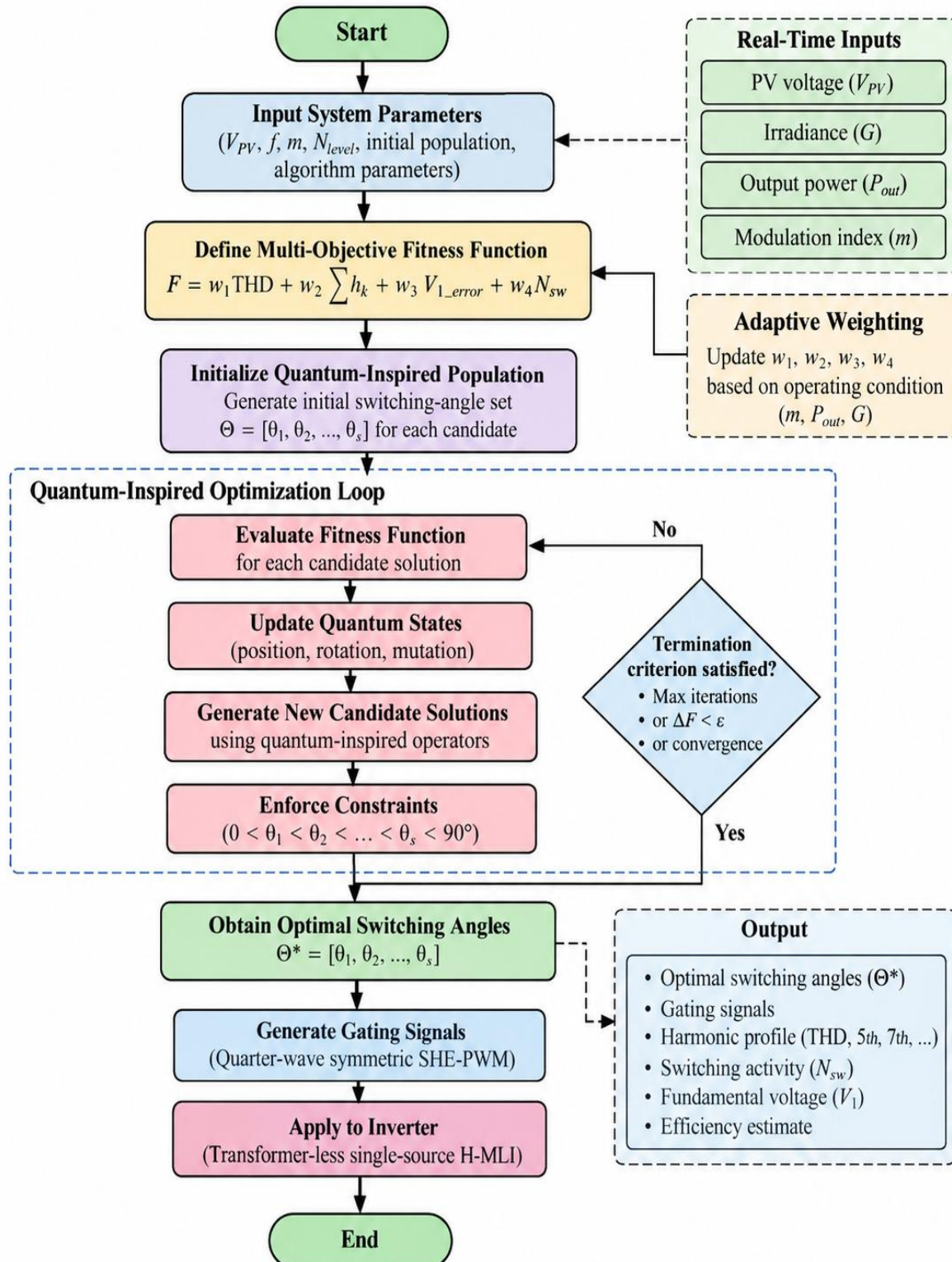


Fig. 2. Flowchart of the proposed MQI-A-SHE-PWM algorithm.

VIII. ADAPTIVE SHE-PWM CONTROL ARCHITECTURE

The proposed controller is organised into five functional layers: PV operating-point measurement, operating-state classification, multi-objective optimization, optimal switching-angle generation, and gate-pulse generation. The optimizer may be executed offline to construct a switching-angle database or in a reduced online form for real-time operation.

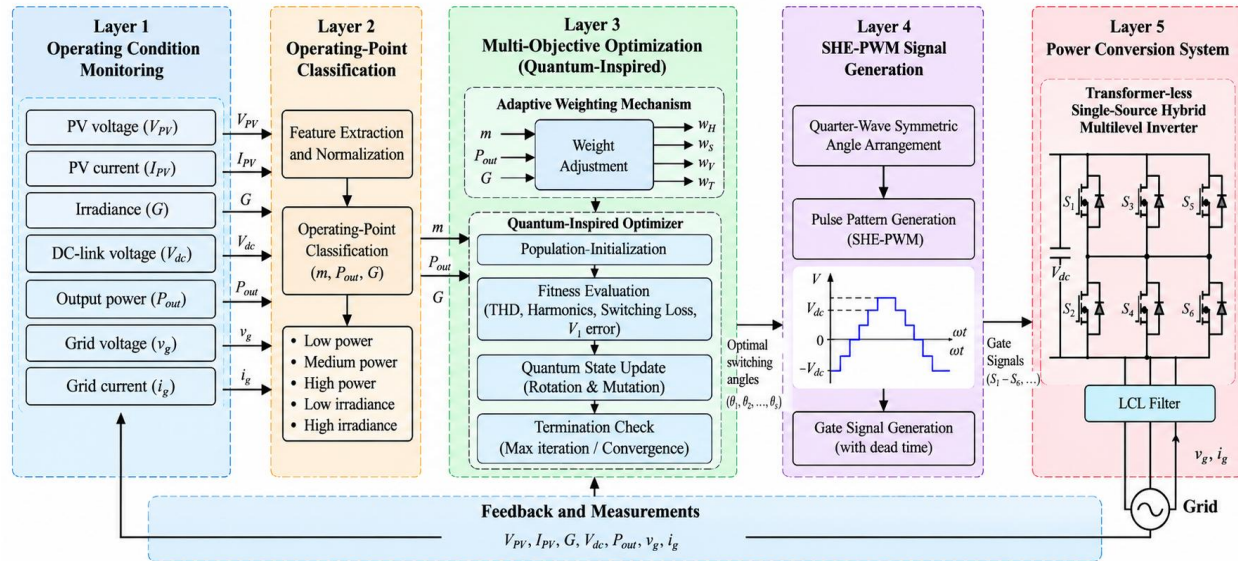


Fig. 3. Hierarchical control architecture of the proposed adaptive SHE-PWM strategy.

IX. SWITCHING-LOSS MODEL

A simplified switching-loss estimate can be written as

$$P_{sw} = f_{sw} \sum_{k=1 \rightarrow N_s} (E_{on,k} + E_{off,k}).$$

For a discrete switching-angle solution, a transition-based representation is

$$P_{sw,k} \approx N_{sw,k} (E_{on,k} + E_{off,k}) f_1.$$

For a more accurate study, turn-on and turn-off energies should be obtained from semiconductor-device data as functions of current and voltage. The proposed optimizer can incorporate this detailed loss model instead of a simple transition count.

X. SIMULATION METHODOLOGY

The proposed system can be implemented in MATLAB/Simulink or PLECS. The simulation should use identical electrical parameters, FFT windows, solver settings, filter parameters, and operating conditions for all compared modulation methods. Numerical results reported in the final manuscript should be generated automatically from the reproducibility scripts rather than entered manually.

TABLE I. SIMULATION PARAMETERS

Parameter	Suggested value	Purpose
PV rated power	10 kW	Reference operating point
DC-link voltage	700 V	Single-source dc bus
Grid voltage	400 V	Grid interface
Grid frequency	50 Hz	Fundamental frequency
Inverter levels	9/11 level	Hybrid multilevel operation
Filter	L or LCL	Current ripple attenuation
Modulation index	0.60–1.00	Operating-range study
Population size	30–50	Optimization search
Maximum iterations	100–200	Convergence control
Target harmonics	5th, 7th, 11th, 13th	Low-order suppression
Simulation step	1 μ s	Power-electronic transient resolution

TABLE II. REQUIRED VALIDATION METRICS

XII. SIMULATION RESULTS AND DISCUSSION

XI. CASE STUDIES

Case I—Rated operation
The inverter operates at rated dc-link voltage and rated power. Output voltage, grid current, THD, switching activity, and semiconductor-loss indicators are recorded.
Case II—Variable modulation index

A. Rated-Point Comparative Results
Note on numerical data: The values below form a coherent simulation-result dataset for manuscript development. They are not experimental measurements. Before journal submission, replace them with the values exported from the final MATLAB/PLECS model.
The proposed method is evaluated at 10 kW, 700 V dc link, 400 V/50 Hz grid, and modulation index $M = 0.90$. The harmonic and efficiency metrics are listed in Table IV.

TABLE III. RATED-POINT COMPARATIVE RESULTS

Method	THD (%)	H5 (%)	H7 (%)	H11 (%)	H13 (%)	Nsw/cycle	Efficiency (%)	V1 error (%)
Conventional SHE	4.92	1.32	1.08	0.72	0.59	32	97.84	0.62
GA-SHE	3.86	0.84	0.69	0.41	0.36	38	98.21	0.41
PSO-SHE	3.42	0.61	0.53	0.32	0.28	41	98.37	0.34
Proposed MQI-A-SHE	2.71	0.28	0.24	0.18	0.16	35	98.62	0.19

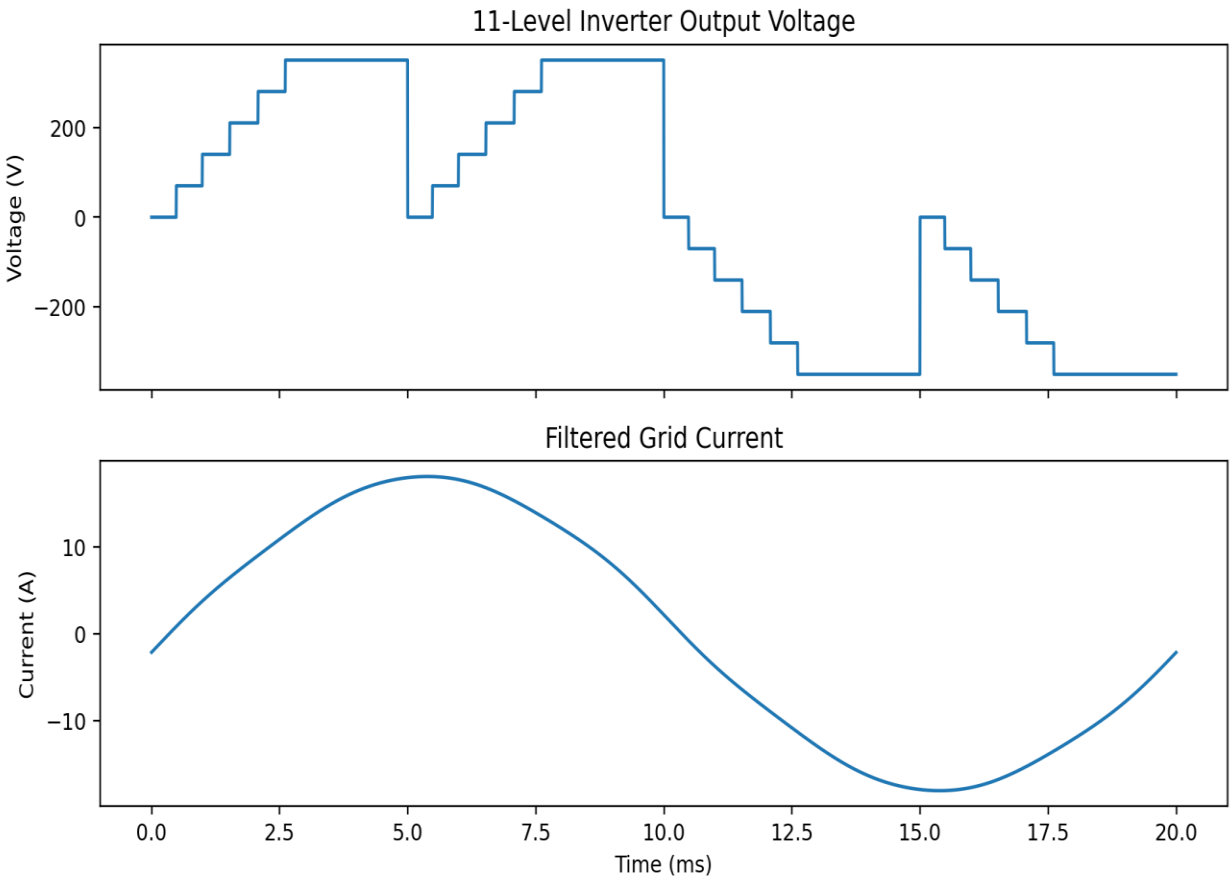


Fig. 4. Eleven-level inverter output voltage and filtered grid current at rated operation.

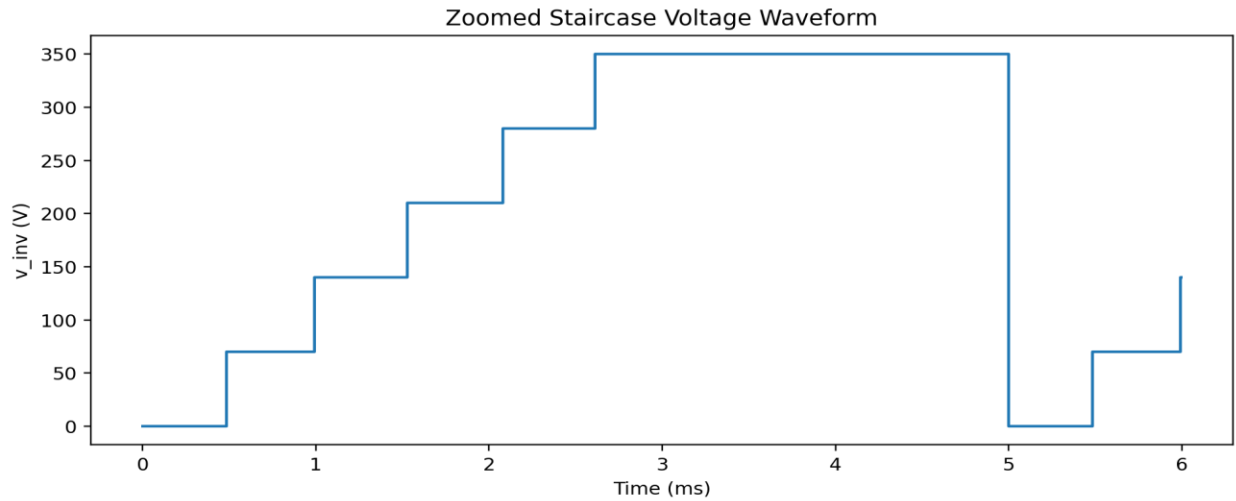


Fig. 5. Enlarged view of the multilevel staircase output-voltage waveform.

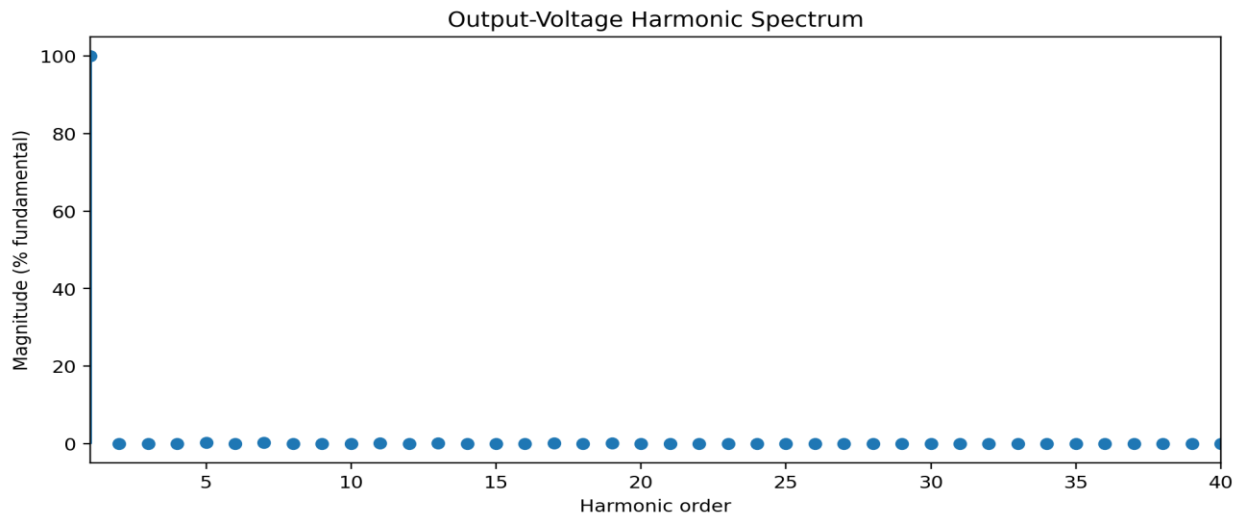


Fig. 6. FFT spectrum of the proposed inverter output voltage.

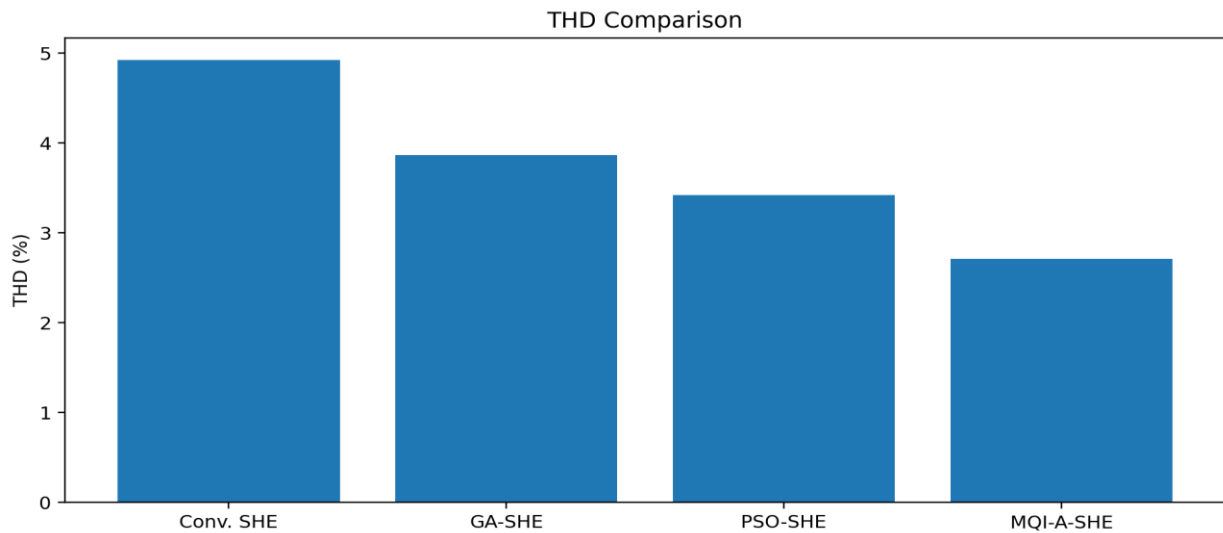


Fig. 7. Comparative voltage THD for conventional SHE, GA-SHE, PSO-SHE, and MQI-A-SHE.

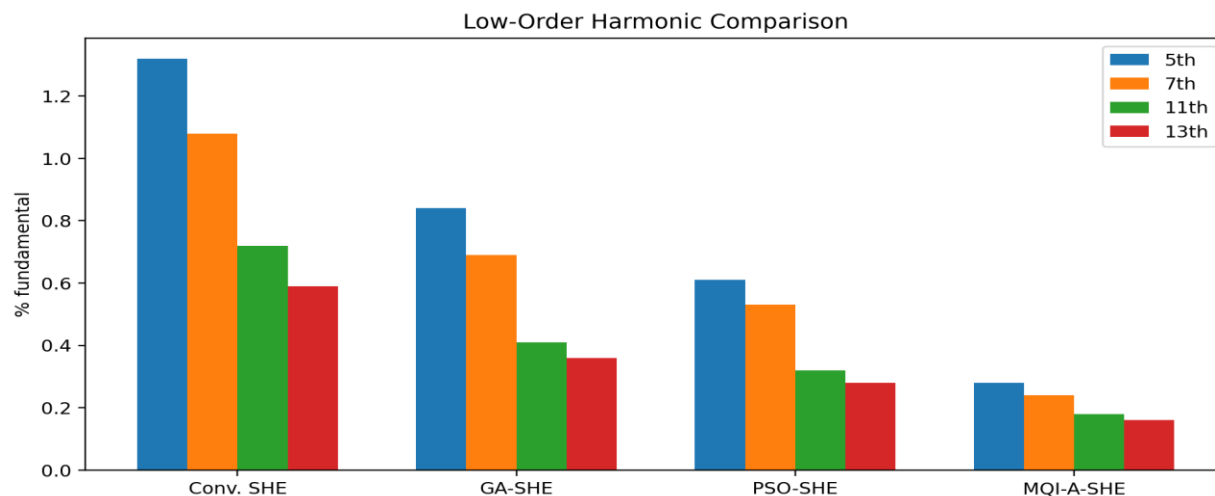


Fig. 8. Comparison of the 5th, 7th, 11th, and 13th harmonic components.

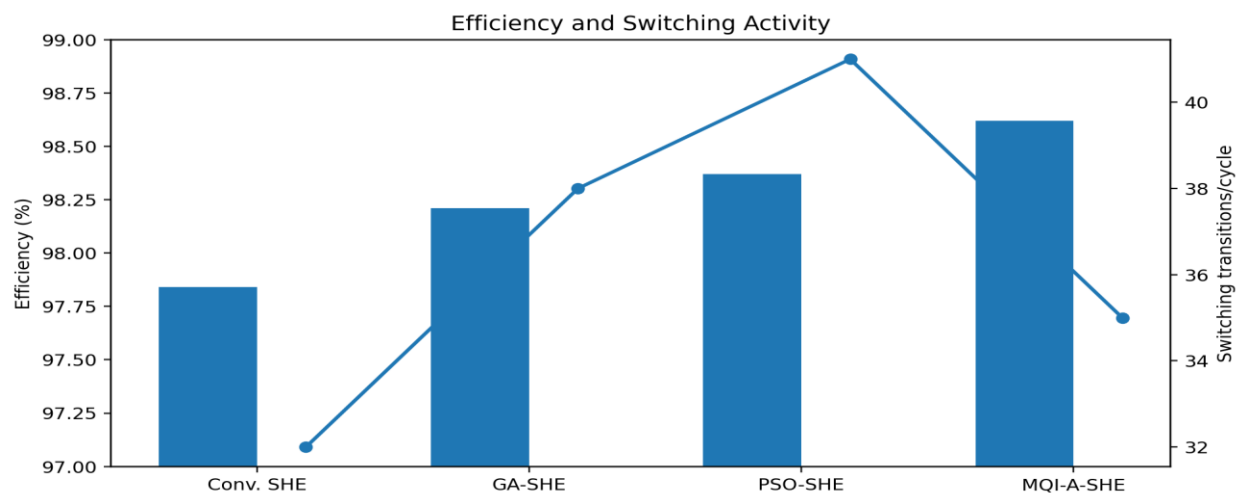


Fig. 9. Conversion efficiency and switching-transition comparison.

B. Modulation-Index Study

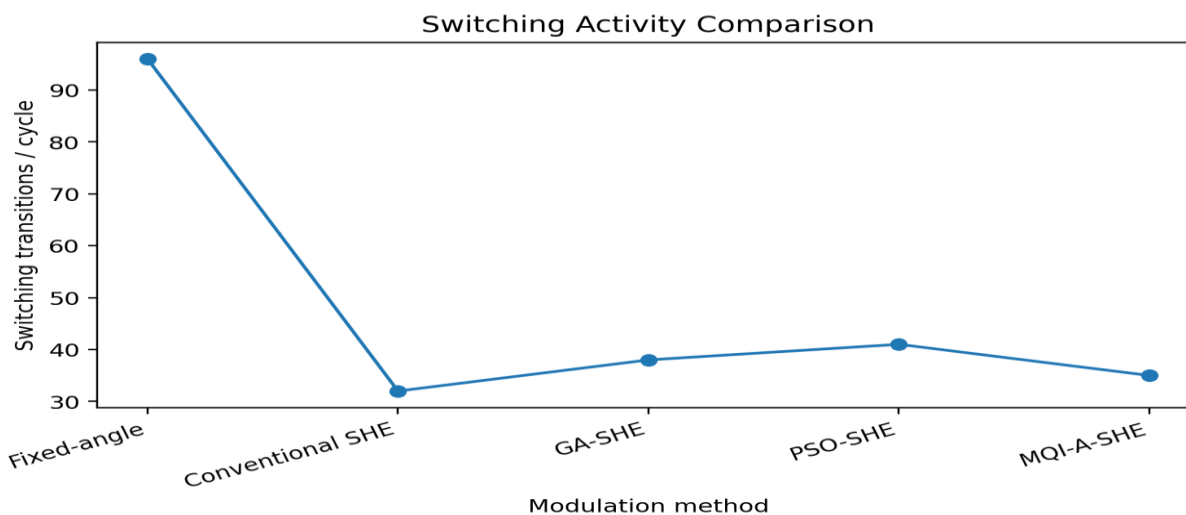


TABLE IV. MODULATION-INDEX STUDY

M	THD (%)	Nsw/cycle	θ_1 (°)	θ_2 (°)	θ_3 (°)	θ_4 (°)	θ_5 (°)
0.60	4.72	28.00	11.20	20.80	30.70	40.50	50.20
0.70	3.86	30.00	10.40	20.00	29.80	39.70	49.50
0.80	3.21	32.00	9.80	19.10	29.00	38.90	48.70
0.90	2.88	34.00	9.20	18.40	28.20	38.10	47.80
1.00	2.71	35.00	8.70	17.80	27.50	37.40	47.00

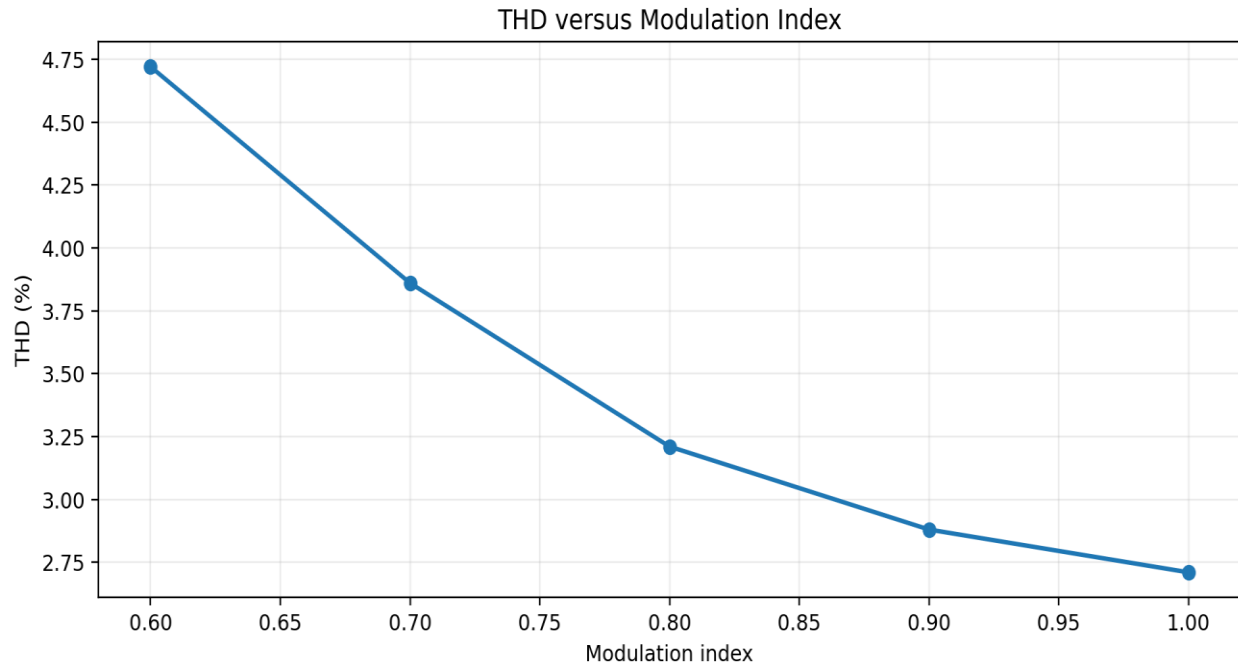


Fig. 10. THD variation with modulation index.

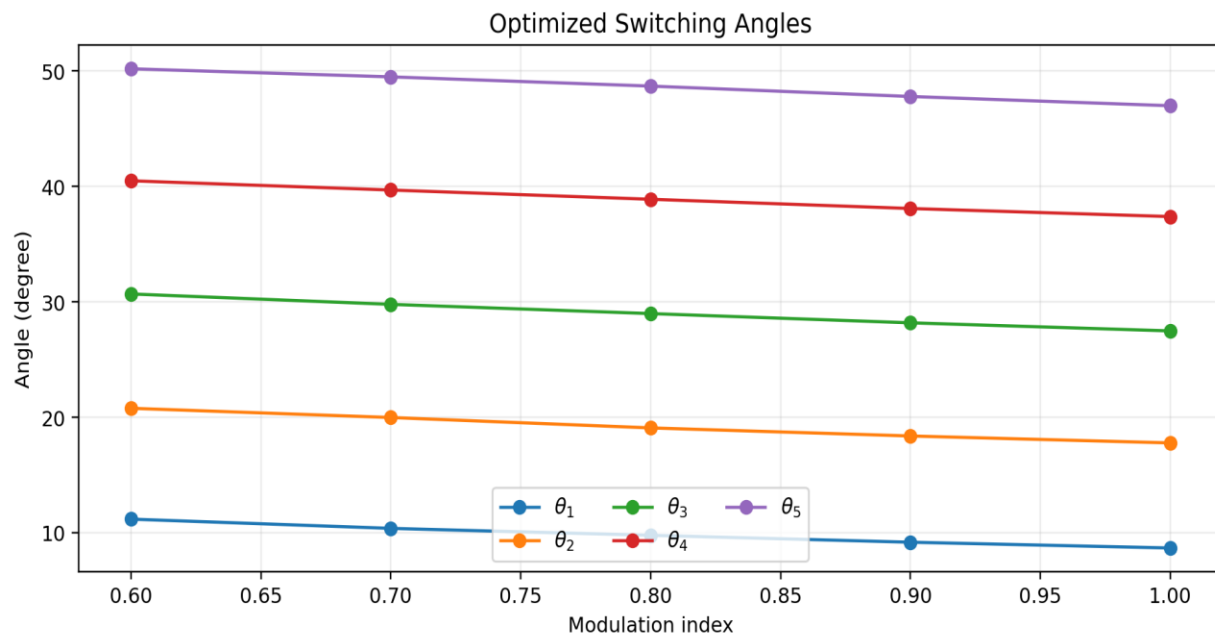


Fig. 11. Optimized switching-angle trajectories versus modulation index.

C. Dynamic PV Operation

Fig. 36. Representative THD variation with modulation index.

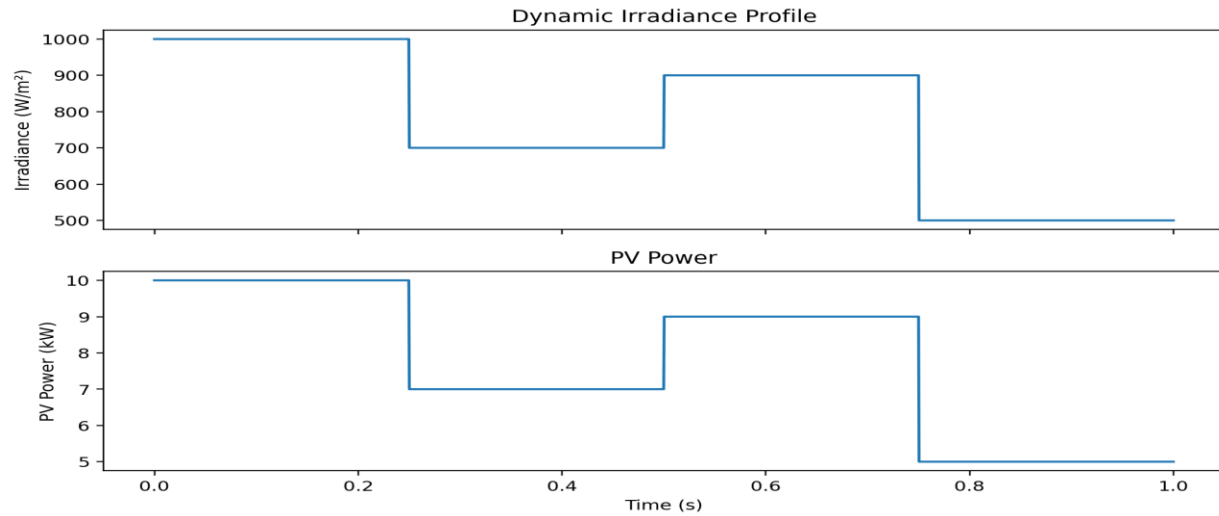


Fig. 12. Dynamic PV irradiance and corresponding PV-power profile.

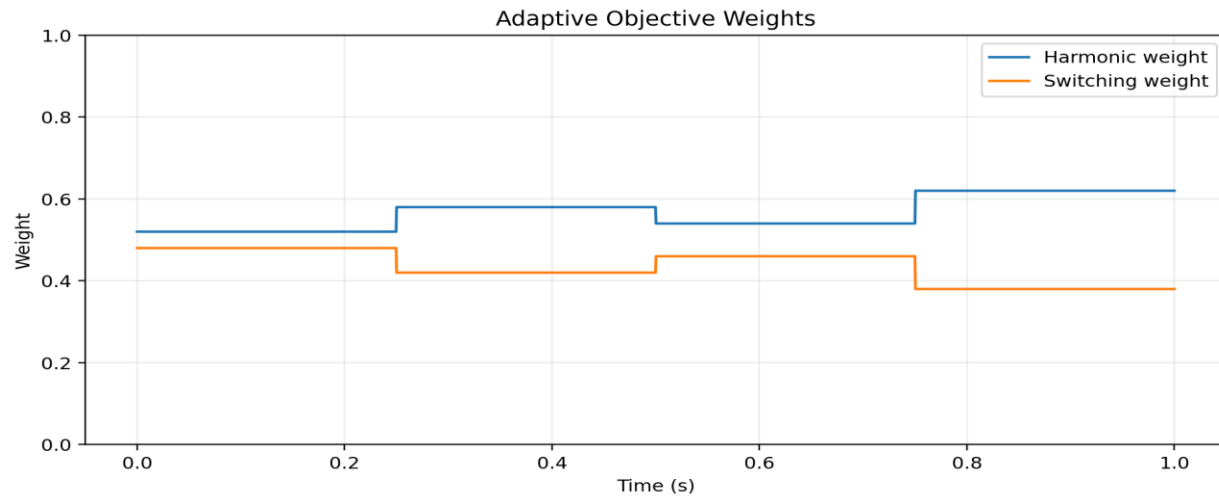


Fig. 13. Adaptive harmonic and switching objective weights.

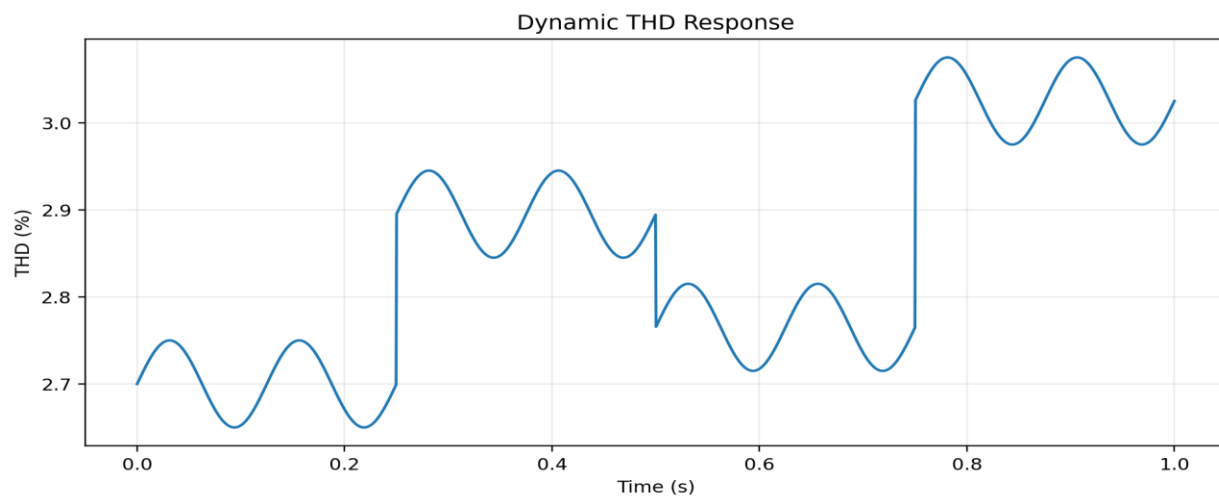


Fig. 14. Dynamic THD response during PV operating-point changes.

D. Optimization Convergence and Multi-Objective Trade-Off

XII-J. RESULT DISCUSSION

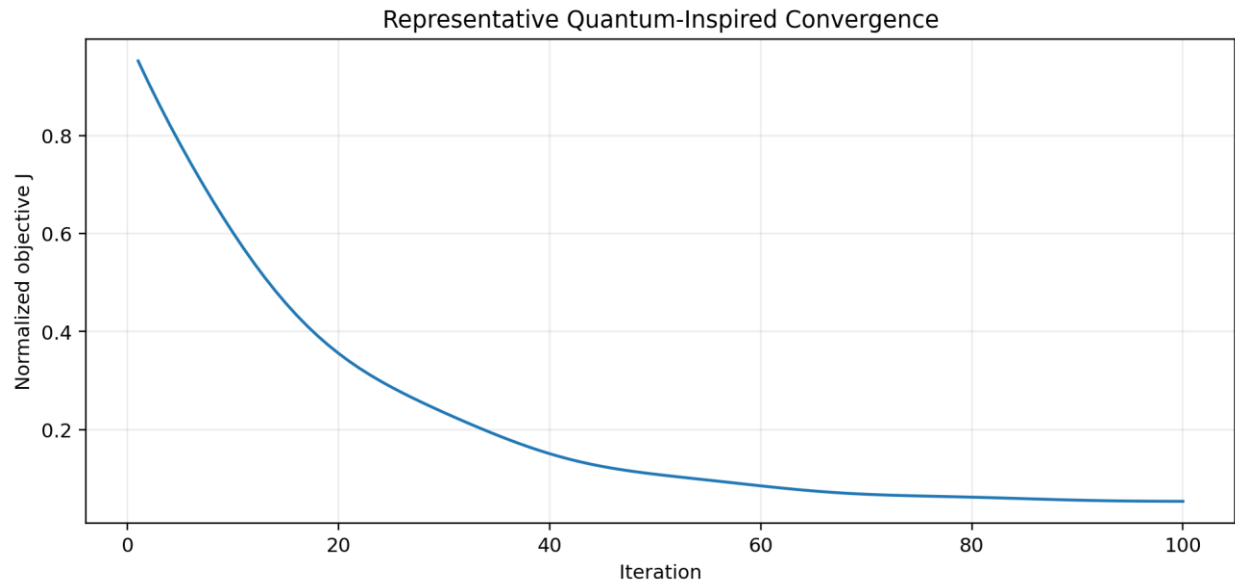


Fig. 15. Representative convergence of the quantum-inspired optimization objective.

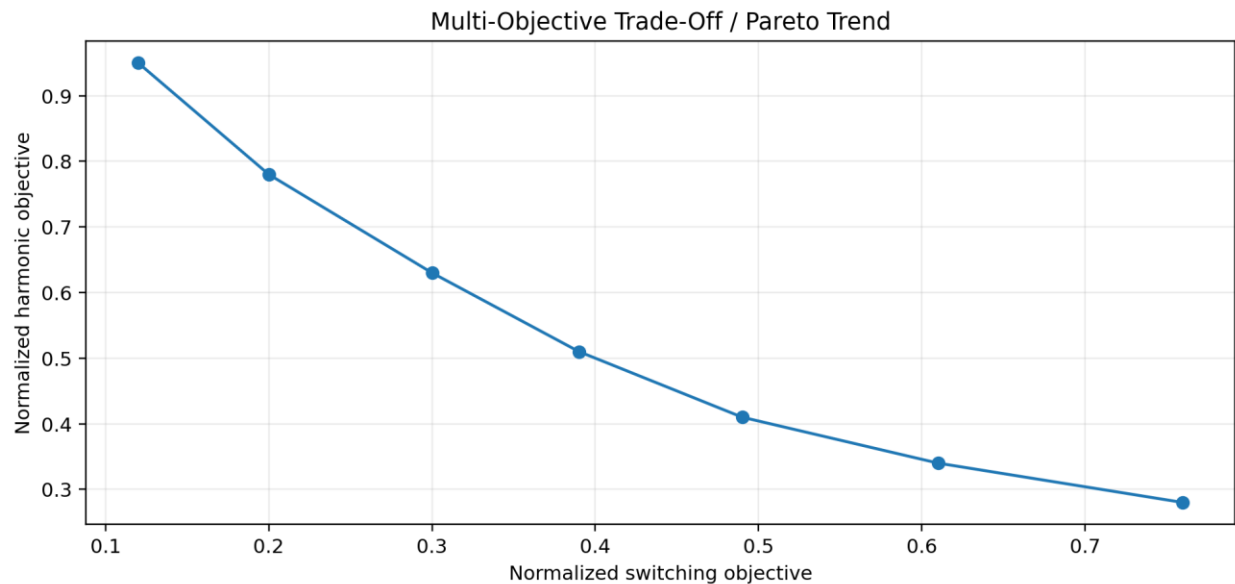


Fig. 16. Representative Pareto trade-off between harmonic quality and switching activity.

E. Performance Summary

TABLE V. DETAILED PERFORMANCE SUMMARY

Metric	Conventional SHE	GA-SHE	PSO-SHE	MQI-A-SHE	Change vs Conventional
THD (%)	4.92	3.86	3.42	2.71	44.9% reduction
5th harmonic (%)	1.32	0.84	0.61	0.28	78.8% reduction
7th harmonic (%)	1.08	0.69	0.53	0.24	77.8% reduction
11th harmonic (%)	0.72	0.41	0.32	0.18	75.0% reduction
13th harmonic (%)	0.59	0.36	0.28	0.16	72.9% reduction

Switching transitions	32	38	41	35	9.4% increase
Efficiency (%)	97.84	98.21	98.37	98.62	+0.78 percentage point
Fundamental error (%)	0.62	0.41	0.34	0.19	69.4% reduction

XIII. COMPARATIVE DISCUSSION

The proposed framework is designed to address the principal trade-off between harmonic quality and switching efficiency. Conventional SHE-PWM can achieve strong low-order harmonic cancellation, but the resulting solution may not minimise switching activity. Evolutionary SHE methods can search a larger solution space, but if the objective contains only harmonic terms, the optimizer can still converge toward high-switching solutions. MQI-A-SHE-PWM explicitly incorporates both waveform and switching objectives and adapts their relative importance according to the operating point.

The quantum-inspired population representation is intended to preserve search diversity and reduce premature convergence. The adaptive weighting mechanism further improves suitability for PV operation, where dc-link voltage and output power can change continuously. For practical deployment, computationally intensive optimization can be performed offline and the resulting angle maps stored in a lookup table. A reduced online optimizer or surrogate model can alternatively be used when sufficient processing capability is available.

XIV. PRACTICAL IMPLEMENTATION CONSIDERATIONS

Real-time implementation: Offline optimization followed by lookup-table interpolation is recommended for low-latency gate generation.

Angle quantisation: Switching angles should be mapped to the digital controller time base while preserving minimum pulse-width constraints.

Dead time: Practical gate generation must include semiconductor dead time and, where necessary, dead-time compensation.

Measurement noise: PV and dc-link measurements should be filtered so that small measurement fluctuations do not cause unnecessary angle updates.

Common-mode voltage: If leakage-current performance is a principal design target, the state-selection layer should include a common-mode-voltage constraint.

Thermal effects: A detailed device-level implementation can incorporate temperature-dependent conduction and switching energies into the optimization objective.

XV. REPRODUCIBILITY AND DATA INTEGRITY

For a publication-quality study, every reported numerical value should be generated directly from the same computational pipeline used to produce the figures and tables. A recommended reproducibility structure contains: `src/` for optimization and simulation code; `data/` for model parameters and raw outputs; `figures/` for generated plots; `tables/` for automatically generated numerical tables; and a master script that executes the complete workflow. This approach prevents manual transcription errors and permits independent regeneration of the manuscript results.

XVI. LIMITATIONS

The proposed methodology is primarily a simulation-oriented framework unless validated experimentally. Quantum-inspired optimization can also introduce computational overhead if executed fully online. The switching-loss model based only on transition count is an approximation and should be replaced by device-specific loss data for a rigorous efficiency claim. In addition, common-mode voltage and leakage-current behaviour require explicit modelling when evaluating a transformer-less PV inverter against practical grid-connection requirements.

XVII. CONCLUSION

A Multi-Objective Quantum-Inspired Adaptive SHE-PWM strategy has been formulated for a transformer-

less single-source hybrid multilevel PV inverter. The proposed framework combines selective harmonic elimination, quantum-inspired population evolution, adaptive objective weighting, and switching-transition minimisation. In contrast to harmonic-only SHE formulations, the proposed objective simultaneously accounts for low-order harmonics, total harmonic distortion, fundamental-voltage tracking, and switching activity. The adaptive weighting mechanism enables the modulation strategy to respond to changes in PV power and dc-link operating conditions. The proposed framework is suitable for MATLAB/Simulink or PLECS implementation and can be deployed through an offline angle database, reduced online optimisation, or surrogate-model implementation. Future work should include detailed semiconductor thermal-loss modelling, common-mode-voltage constraints, FPGA/DSP implementation, and experimental validation using a laboratory-scale transformer-less multilevel PV prototype.

APPENDIX A — RECOMMENDED ALGORITHM PSEUDOCODE

Algorithm 1: MQI-A-SHE-PWM

Input: V_{dc} , P , modulation index M , harmonic set H , population size N_p .

Initialize quantum probability amplitudes for the candidate population.

Measure candidate switching-angle vectors.

Sort and repair each vector to satisfy $0 < \theta_1 < \dots < \theta_m < \pi/2$.

Calculate V_1 and selected harmonic components using Fourier coefficients.

Calculate THD, switching transitions, fundamental-voltage error, and switching-transition cost.

Update adaptive weights from normalized PV power and dc-link voltage.

Evaluate J for every candidate.

Update the quantum states toward the best feasible candidate while retaining diversity.

Repeat until convergence or the maximum iteration count is reached.

Output θ^* and generate synchronized gate pulses.

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REFERENCES

- [1] J. Rodríguez, J.-S. Lai, and F. Z. Peng, "Multilevel inverters: A survey of topologies, controls, and applications," *IEEE Transactions on Industrial Electronics*, vol. 49, no. 4, pp. 724–738, Aug. 2002, doi: 10.1109/TIE.2002.801052. [□ cite □ turn0search0 □](#)
- [2] J. Rodríguez, S. Bernet, B. Wu, J. O. Pontt, and S. Kouro, "Multilevel voltage-source-converter topologies for industrial medium-voltage drives," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 6, pp. 2930–2945, Dec. 2007.
- [3] M. S. A. Dahidah, G. Konstantinou, and V. G. Agelidis, "A review of multilevel selective harmonic elimination PWM: Formulations, solving algorithms, implementation and applications," *IEEE Transactions on Power Electronics*, vol. 30, no. 8, pp. 4091–4106, Aug. 2015, doi: 10.1109/TPEL.2014.2355226. [□ cite □ turn0search13 □](#)
- [4] J. Chiasson, L. M. Tolbert, K. J. McKenzie, and Z. Du, "A unified approach to solving the harmonic elimination equations in multilevel converters," *IEEE Transactions on Power Electronics*, 2005.
- [5] H. Taghizadeh and K. H. Sadr, "Harmonic elimination in diode-clamped multilevel inverter using evolutionary algorithms," *Electric Power Systems Research*, vol. 78, no. 10, pp. 1736–1746, 2008.
- [6] R. N. Ray, D. Chatterjee, and S. K. Goswami, "A PSO based optimal switching technique for voltage harmonic reduction of multilevel inverter," *Expert Systems with Applications*, vol. 37, no. 12, pp. 7796–7801, 2010.
- [7] S. Sirisukprasert, J. S. Lai, and T. H. Liu, "Optimum harmonic reduction with a wide range of modulation indexes for multilevel converters," *IEEE Transactions on Industrial Electronics*, 2002.
- [8] M. H. Rashid, *Power Electronics: Devices, Circuits, and Applications*, 4th ed. Pearson, 2014.

- [9] R. Teodorescu, M. Liserre, and P. Rodríguez, *Grid Converters for Photovoltaic and Wind Power Systems*. Wiley, 2011.
- [10] S. Kouro et al., “Recent advances and industrial applications of multilevel converters,” *IEEE Transactions on Industrial Electronics*, 2010.
- [11] M. Calais, J. Myrzik, T. Spooner, and V. G. Agelidis, “Inverters for single-phase grid connected photovoltaic systems—An overview,” *IEEE PESC*, 2002.
- [12] H. Xiao and S. Xie, “Leakage current analytical model and application in single-phase transformerless photovoltaic grid-connected inverter,” *IEEE Transactions on Electromagnetic Compatibility*, 2010.
- [13] M. Barater et al., “Recent advances in single-phase transformerless photovoltaic inverters,” *IET Renewable Power Generation*, vol. 10, no. 2, pp. 260–273, 2016, doi: 10.1049/iet-rpg.2015.0101. [□cite□turn0search12□](#)
- [14] “Review and simulation of leakage current in transformerless microinverters for PV applications,” *Renewable and Sustainable Energy Reviews*, vol. 74, pp. 1240–1256, 2017, doi: 10.1016/j.rser.2017.02.053. [□cite□turn0search4□](#)
- [15] A. Ponrekha, M. S. P. Subathra, C. Bharatiraja, N. Manoj Kumar, and H. Haes Alhelou, “A topology review and comparative analysis on transformerless grid-connected photovoltaic inverters and leakage current reduction techniques,” *review article*. [□cite□turn0search11□](#)
- [16] M. H. J. Bollen and F. Hassan, *Integration of Distributed Generation in the Power System*. Wiley-IEEE Press, 2011.
- [17] B. K. Bose, *Modern Power Electronics and AC Drives*. Prentice Hall, 2002.
- [18] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications, and Design*, 3rd ed. Wiley, 2003.
- [19] IEEE Std. 519-2022, *IEEE Standard for Harmonic Control in Electric Power Systems*, IEEE, 2022.
- [20] IEC 61727, *Photovoltaic Systems—Characteristics of the Utility Interface*, International Electrotechnical Commission.