



Hybrid Chaotic–Lévy Flight Artificial Bee Colony Optimization for Selective Harmonic Elimination in a 31-Level Asymmetric Cascaded H-Bridge Inverter

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ABSTRACT.

Harmonic distortion limits the power quality of multilevel inverters, and selective harmonic elimination (SHE) becomes a difficult, high-dimensional nonlinear problem as the number of voltage levels grows. This paper compares three Artificial Bee Colony (ABC) variants for computing the switching angles of a single-phase, 31-level asymmetric cascaded H-bridge inverter: a chaotic-map ABC, a Lévy-flight ABC, and a proposed hybrid that blends the two search mechanisms through a linearly annealed weight. The inverter, built from five H-bridges and 20 IGBTs, was modelled in MATLAB/Simulink and evaluated at six modulation indices (0.60–0.85), with and without an L-C-L output filter, using ten independent optimization runs per algorithm. The hybrid gave the lowest unfiltered total harmonic distortion (THD) at every modulation index, averaging 4.31 % against 4.95 % (chaotic) and 4.84 % (Lévy), and exceeded the 5 % IEEE 519-2022 limit at one modulation index instead of two or three. With the filter, hybrid THD fell to 0.04–0.22 % (mean 0.10 %), compared with means of 0.24 % and 0.19 % for the standalone variants. Nine of ten hybrid runs converged to final fitness values between 4.39×10^{-2} and 9.89×10^{-2} ; however, the hybrid was given a larger iteration budget (5,000 versus 100), so part of its advantage may reflect that budget. The asymmetric topology produced all 31 levels with 20 switches rather than about 60 for a symmetric design. The results suggest that combining chaotic and Lévy-flight search inside ABC is a promising route to low-distortion, standards-compliant high-level inverters.

Keywords: multilevel inverter; selective harmonic elimination; artificial bee colony; chaotic map; Lévy flight; total harmonic distortion; IEEE 519-2022

1. Introduction

Multilevel inverters (MLIs) synthesise a staircase output voltage from several lower-voltage DC sources. Compared with two-level inverters they impose lower voltage stress on each switch, produce lower dv/dt , and need smaller output filters, which is why they are widely used in photovoltaic and wind conversion, motor drives and grid-connected converters [1–4]. Among the classical topologies, the cascaded H-bridge (CHB) is the most modular, and its asymmetric form, in which the isolated DC sources have unequal magnitudes, produces many more output levels from a given number of bridges [2, 5].

Even so, the output of an MLI is never a perfect sinusoid. The finite number of levels, imprecise switching angles, DC-source imbalance, dead time and device non-idealities all leave residual harmonics that increase losses, overheat transformers and machines, produce torque ripple and electromagnetic interference, and can excite network resonances [4, 6]. Grid-connected equipment must also respect harmonic limits such as IEEE 519-2022, which recommends a voltage THD below 5 % at the point of common coupling for low-voltage systems [7].

Selective harmonic elimination pulse-width modulation (SHE-PWM) addresses this by choosing the switching angles so that selected low-order harmonics vanish while the fundamental is held at its reference value. It works at the fundamental switching frequency, which keeps switching losses low, but it requires solving a set of coupled transcendental equations [8, 9]. Newton-type solvers are sensitive to the initial guess and become unreliable as the number of angles increases [9, 10], so metaheuristics such as genetic algorithms, particle swarm optimization and several newer swarm methods have been used instead [11]. Their common weaknesses are slow or premature convergence, sensitivity to tuning parameters and degraded performance as the dimension grows.

The Artificial Bee Colony (ABC) algorithm [12] is attractive for this task because it has few control parameters and a built-in balance between exploration (scout bees) and exploitation (employed and onlooker bees). Comparative studies report that ABC outperforms GA and PSO for 27- and 31-level inverters [13, 14]. Standard ABC can nevertheless stagnate and refine solutions slowly. Chaotic sequences can enrich population diversity and speed up convergence [15], while Lévy flights add occasional long jumps that help the search leave local optima [16, 17]. The two mechanisms are complementary, and hybridizing ABC with other search strategies has already shown gains in harmonic minimization [18]. To the best of our knowledge, however, their combination inside ABC has not been evaluated for SHE at the 31-level scale.

This paper makes four contributions:

- It formulates SHE for a 31-level, 15-angle problem on a five-bridge asymmetric CHB inverter that uses only 20 switches.
- It proposes a hybrid ABC update rule that blends a chaotic perturbation and a Lévy-flight jump through a weight $\lambda(t)$ annealed from exploration-dominant to exploitation-dominant.
- It reports a like-for-like comparison with standalone chaotic and Lévy-flight ABC at six modulation indices, with and without an L-C-L filter, over ten independent runs per algorithm, judged against IEEE 519-2022.
- It states plainly where the hybrid helps (low and mid modulation indices) and where it does not (the upper end of the range), and which parts of the comparison are confounded by unequal iteration budgets.

Section 2 reviews related work, Section 3 presents the inverter and the SHE formulation, Section 4 describes the hybrid algorithm, Section 5 gives the simulation set-up, Section 6 discusses the results, and Section 7 concludes.

2. Related Work

Table 1 summarises representative studies that apply optimization to harmonic minimization in MLIs. Three observations stand out. First, ABC-based methods are consistently competitive: ABC beat PSO and a flower-pollination algorithm on a reduced-switch 15-level PV inverter [19], and beat GA on 27- and 31-level asymmetric inverters [13]. Second, hybridization usually helps. An ABC–firefly hybrid reached THD below 5 % on a 21-level asymmetric CHB and improved on its standalone components by 10–20 % [18], and hybrids of metaheuristics with recurrent neural networks reported faster convergence and better harmonic suppression [20, 21]. Third, the highest-level cases remain thinly covered. The lowest 31-level THD we found, 2.30 %, was obtained by biogeography-based optimization checked against a Newton–Raphson solution [22], but without a filter stage and with limited reporting across modulation indices.

Table 1. Representative studies on optimization-based harmonic minimization in multilevel inverters.

Study	Topology / domain	Method	Reported outcome
[18]	21-level asymmetric CHB	Hybrid ABC–firefly	THD < 5 %; 10–20 % better than standalone ABC and FA
[19]	15-level reduced-switch, PV	ABC vs PSO, FPA	THD 4.86 % with ABC, best of the three
[22]	31-level cascaded	BBO vs Newton–Raphson	THD as low as 2.30 %
[13]	27- and 31-level asymmetric	ABC vs GA	ABC gave lower THD than GA
[23]	11-level reduced-switch	Hybrid TLBO–WOA	Better THD than standalone methods; simulation and experiment
[20] [21]	Multilevel inverters	Metaheuristic + enhanced RNN	Faster convergence and better harmonic suppression
[15]	Power systems (optimal power flow)	Chaotic ABC	Faster convergence, less stagnation than standard ABC
[16]	Swarm optimizers, inverter problems	Lévy-flight integration	Greater diversity and reduced THD

PV, photovoltaic; FPA, flower pollination algorithm; BBO, biogeography-based optimization; TLBO, teaching–learning-based optimization; WOA, whale optimization algorithm; RNN, recurrent neural network.

Chaos and Lévy flights have each been studied separately. A chaotic ABC converged faster and stagnated less than standard ABC on optimal power flow [15], and Lévy-flight integration increased solution diversity in swarm optimizers [16]. Both results come from outside high-level MLI harmonic

minimization, and none of the works we surveyed compares the two mechanisms, alone and combined, on the same 31-level SHE problem. Reviews also note that many MLI optimization studies are validated by simulation only and give limited attention to the computational difficulty of high-level cases [11, 24]. The present study is also simulation-only, but it covers a modulation-index range, an explicit filter stage and ten-run convergence spread.

3. Inverter Model and SHE Formulation

3.1 Topology and overall framework

The system studied is a single-phase asymmetric CHB inverter made of five H-bridge modules, each fed by its own isolated DC source and containing four IGBTs with anti-parallel diodes, for 20 controlled switches (T1–T20). The bridge outputs are summed in series. Each bridge can produce $+V_k$, 0 or $-V_k$, and the five source magnitudes are chosen so that their signed combinations cover every integer multiple of a voltage step V_s from $-15V_s$ to $+15V_s$, giving 31 levels. A symmetric CHB with equal sources would need 15 bridges and 60 switches for the same 31 levels. The inverter output feeds an L-C-L filter in the filtered cases. Fig. 1 shows the complete framework: the optimizer computes the angles, a switching-state table converts them to gate signals, and the simulated inverter output is analysed by FFT.

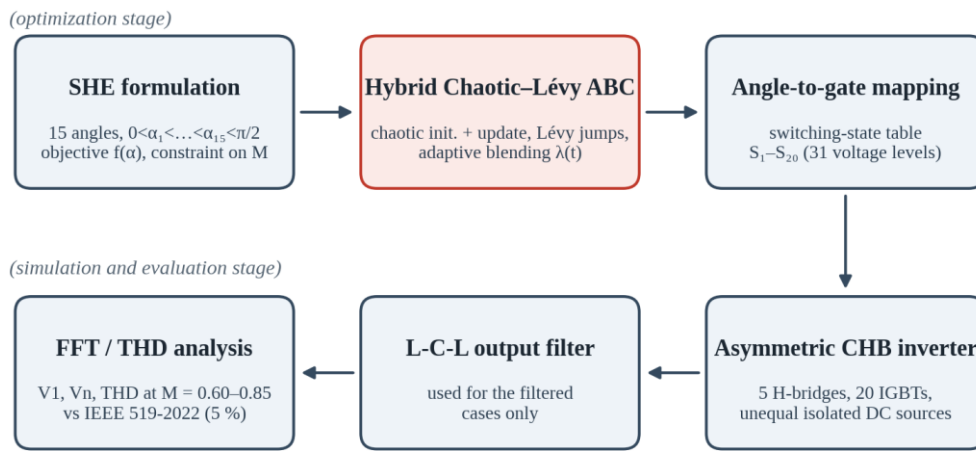


Fig. 1. Framework of the proposed system: SHE formulation, hybrid chaotic-Lévy ABC optimization, angle-to-gate mapping, the five-bridge asymmetric CHB inverter, the L-C-L filter (filtered cases only), and FFT/THD evaluation.

3.2 Fourier model and harmonic equations

With quarter-wave symmetry, the staircase output has only odd harmonics. A waveform with $m = 15$ switching angles $0 < \alpha_1 < \alpha_2 < \dots < \alpha_{15} < \pi/2$ has the harmonic amplitudes

$$V_n = \frac{4V_s}{n\pi} \sum_{k=1}^{15} \cos(n\alpha_k), \quad n = 1, 3, 5, \dots \quad (1)$$

The fundamental follows from $n = 1$, and the modulation index M is defined by the normalised sum of the cosines,

$$V_1 = \frac{4V_s}{\pi} \sum_{k=1}^{15} \cos\alpha_k, \quad \frac{1}{15} \sum_{k=1}^{15} \cos\alpha_k = M \quad (2)$$

The SHE conditions require the selected low-order harmonics to vanish while the fundamental satisfies Eq. (2):

$$\sum_{k=1}^{15} \cos(n\alpha_k) = 0, \quad n = 3, 5, 7, \dots \quad (3)$$

Because the transcendental system (3) is nonlinear and multimodal in 15 variables, it is solved here by optimization. The performance index is the voltage THD,

$$THD = \frac{\sqrt{\sum_{n=3,5,7}^{\infty} V_n^2}}{V_1} \times 100\% \quad (4)$$

and the objective minimised by the ABC variants is the harmonic-energy measure

$$f(\alpha_1, \dots, \alpha_{15}) = \sum_{n=3,5,7}^{N_h} \left[\frac{1}{n} \sum_{k=1}^{15} \cos(n\alpha_k) \right]^2 \quad (5)$$

where N_h is the highest harmonic order considered. Since $V_n/(4V_s/\pi) = (1/n) \sum \cos(n\alpha_k)$, f is proportional to the squared harmonic content relative to a unit fundamental, so minimising f at a fixed modulation index minimises THD. The angle bounds and ordering are enforced after every update.

3.3 Switching states and gate generation

For each of the 31 output levels there is a fixed gating pattern for S1–S20. Gate signals are produced by comparing the electrical angle with the optimized angle set: the number of angles already passed fixes the instantaneous level, and the matching row of the switching-state table drives the 20 IGBTs. The table is determined by the topology alone, so the three algorithms differ only in the angular positions of the transitions. This isolates the effect of the optimizer from every other part of the system.

4. Hybrid Chaotic–Lévy Flight ABC

4.1 Standard ABC

In ABC each food source is a candidate angle vector $\mathbf{x}_i = (x_{i1}, \dots, x_{i15})$, and the colony consists of employed bees, onlooker bees and scouts. Employed bees perturb their own source using a randomly chosen peer k and keep the better of the old and new positions. Onlookers then select sources with probability proportional to fitness and refine them in the same way. A source that fails to improve for a set number of trials is abandoned and replaced by a scout. With f_i the objective of Eq. (5), the fitness is

$$fit(f_i) = \frac{1}{1 + f_i}, \quad f_i \geq 0 \quad (6)$$

4.2 Chaotic component

The standard neighbourhood move uses a uniform random coefficient $\phi \in [-1, 1]$. The chaotic variant draws its coefficient from a logistic map,

$$c_{t+1} = r c_t (1 - c_t), \quad r = 4 \quad (7)$$

which is deterministic, never repeats, and covers (0, 1) more evenly in the long run than clustered pseudo-random draws (Fig. 2a). The candidate position becomes

$$v_{ij} = x_{ij} + c_{ij}(t)(x_{ij} - x_{kj}) \quad (8)$$

where v_{ij} is the trial value of dimension j , $k \neq i$ indexes a random peer, and $c_{ij}(t)$ is the chaotic value that replaces ϕ . This component supplies the fine, ergodic local search.

4.3 Lévy-flight component

Lévy-flight steps have a heavy-tailed density $L(s) \sim |s|^{-1-\beta}$ with $0 < \beta \leq 2$, so most moves are small but long jumps occur with non-negligible probability (Fig. 2b). They are generated with Mantegna's algorithm [17],

$$s = \frac{u}{|v|^{\frac{1}{\beta}}}, \quad u \sim N(0, \sigma_u^2), \quad v \sim N(0, 1) \quad (9)$$

$$\sigma_u = \left[\frac{\Gamma(1+\beta) \sin(\frac{\pi\beta}{2})}{\Gamma(\frac{1+\beta}{2}) \beta 2^{\frac{\beta-1}{2}}} \right]^{\frac{1}{\beta}} \quad (10)$$

The step is applied relative to the global best source $\mathbf{x}^{best}$:

$$v_{ij} = x_{ij} + \alpha L_j(\beta)(x_{ij} - x_j^{best}) \quad (11)$$

This component supplies global exploration and the ability to escape local optima.

4.4 Hybrid update with adaptive blending

The proposed update blends the two moves with a weight λ that decreases linearly from λ_{max} to λ_{min} :

$$v_{ij} = (1 - \lambda)[x_{ij} + c_{ij}(x_{ij} - x_{kj})] + \lambda[x_{ij} + \alpha L_j(\beta)(x_{ij} - x_j^{best})] \quad (12)$$

$$\lambda(t) = \lambda_{max} - (\lambda_{max} - \lambda_{min}) \frac{t}{T_{max}} \quad (13)$$

With $\lambda_{max} = 0.9$ and $\lambda_{min} = 0.1$, the search is Lévy-dominant early, when wide coverage matters, and chaotic-dominant late, when the colony should refine a promising basin (Fig. 2c). The extra cost over standard ABC is one logistic value and one Lévy sample per updated dimension, and no additional objective evaluations are needed because both moves replace the standard neighbourhood move.

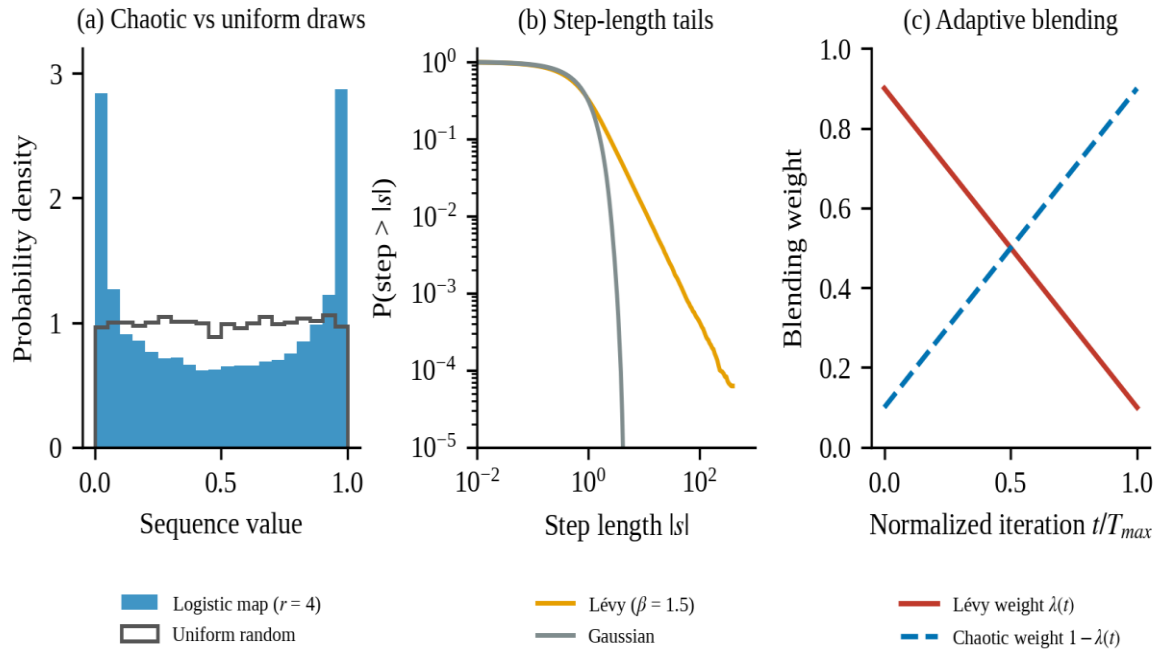


Fig. 2. Behaviour of the search operators. (a) Logistic-map values ($r = 4$) compared with uniform random draws, shown as histograms. (b) Complementary cumulative distribution of Lévy ($\beta = 1.5$) and Gaussian step lengths, showing the heavy Lévy tail. (c) Linearly annealed weights of the Lévy and chaotic components in Eq. (12).

4.5 Algorithm outline

1. Initialise the colony: generate chaotic angle vectors within $(0, \pi/2)$, enforce ordering, and evaluate Eq. (5).
2. Employed-bee phase: for each source, form the hybrid trial of Eq. (12) with the current $\lambda(t)$ from Eq. (13), apply bounds and ordering, and keep the better of the trial and the current source.
3. Onlooker phase: select sources with probability proportional to fitness (Eq. 6) and repeat the hybrid move.
4. Scout phase: replace any source that has not improved within the trial limit.
5. Record the global best; if the iteration budget is not exhausted, return to step 2. Otherwise pass the best angle set to the Simulink model.

4.6 Design rationale and expected behaviour

The blending weight sets the balance between the two moves. At $\lambda = 0.9$ the Lévy term carries 90 % of the weight, so early iterations behave like a best-guided random walk with occasional long jumps, whereas at $\lambda = 0.1$ the move is mostly chaotic and local. The Lévy exponent β controls the tail: smaller β gives heavier tails and more frequent large jumps, while the scale α keeps typical steps small relative to the $(0, \pi/2)$ angle range. One property of the chaotic component deserves attention. The invariant density of the logistic map at $r = 4$ is not uniform but U-shaped (Fig. 2a), so chaotic coefficients fall near 0 and 1 more often than near 0.5. Because $c_{ij} \in (0, 1)$ is not rescaled to $[-1, 1]$, Eq. (8) also pushes a source away from its peer rather than symmetrically around it. These properties can help or hinder depending on the landscape, and they are one possible reason why the standalone chaotic variant produced both very good and very poor runs.

5. Simulation Set-up

The inverter was implemented in MATLAB/Simulink as in Section 3, and the optimizers were coded in MATLAB. The same topology and switching-state table were used for all three algorithms. For every algorithm the inverter was simulated at $M = 0.60, 0.65, 0.70, 0.75, 0.80$ and 0.85 at a 50 Hz fundamental, first without a filter and then with the L-C-L filter, and the voltage THD and fundamental were read from an FFT of the output voltage. Convergence was recorded as the best fitness at each iteration over ten independent runs. Table 2 lists the settings. The standalone chaotic and Lévy-flight variants were each run for 100 iterations and the hybrid for 5,000, a difference that is discussed in Section 6.6.

Table 2. Simulation and algorithm settings. Highlighted entries are to be completed or confirmed against the simulation files.

Item	Setting
Topology	Single-phase asymmetric CHB, five H-bridges, 20 IGBTs (T1–T20)
Output levels	31 ($-15V_s$ to $+15V_s$)
DC sources	Five isolated, unequal: [16V, 32V, 48, 48V, 64V, 80V]
Switching angles	15 per quarter wave, $0 < \alpha_1 < \dots < \alpha_{15} < \pi/2$
Fundamental frequency	50 Hz
Modulation indices	0.60, 0.65, 0.70, 0.75, 0.80, 0.85
Output filter	L-C-L: [500uH, 10000uF]
Load	100kW
Runs per algorithm	10 independent runs
Iterations	100 (chaotic, Lévy-flight); 5,000 (hybrid)
Colony size; scout limit	200
Chaotic map	Logistic, $r = 4$
Lévy parameters	$\beta = 1.5$, $\alpha = 0.01$
Hybrid blending	$\lambda_{\max} = 0.9$, $\lambda_{\min} = 0.1$, linear annealing (Eq. 13)

6. Results and Discussion

6.1 Unfiltered harmonic performance

Table 3 and Fig. 3a give the THD at each modulation index. The hybrid algorithm produced the lowest unfiltered THD at all six modulation indices. Its mean was 4.31 %, against 4.95 % for the chaotic and 4.84 % for the Lévy-flight variant, reductions of 12.9 % and 10.9 % respectively. The advantage is not uniform. Over the better standalone variant at each index, the hybrid's margin ranges from 1.28 percentage points at $M = 0.60$ (4.48 % versus 5.76 %) down to 0.02 points at $M = 0.80$ (3.85 % versus 3.87 %). At $M = 0.75$ –0.80 all three algorithms agree to within about 0.1 points, between 3.81 % and 3.95 %, so the gain from hybridization is concentrated at the lower end of the range. Table 4 lists the margin at every index.

Table 3. Voltage THD (%) at each modulation index, before and after the L-C-L filter. Bold marks the lowest value in each row and condition.

M	Chaotic ABC		Lévy-flight ABC		Hybrid ABC	
	Unf.	Filt.	Unf.	Filt.	Unf.	Filt.
0.60	6.18	0.20	5.76	0.19	4.48	0.08
0.65	4.84	0.16	5.18	0.19	4.61	0.08
0.70	4.89	0.19	4.43	0.17	3.89	0.04
0.75	4.16	0.13	3.95	0.15	3.81	0.06
0.80	3.89	0.70	3.87	0.15	3.85	0.12
0.85	5.75	0.08	5.83	0.26	5.23	0.22

Unf., without filter; Filt., with L-C-L filter. Values above the 5 % IEEE 519-2022 limit occur only in the unfiltered columns.

Table 4. Margin of the hybrid ABC over each standalone variant, in percentage points of THD

M	Unfiltered		With L-C-L filter	
	vs chaotic	vs Lévy	vs chaotic	vs Lévy
0.60	+1.70	+1.28	+0.12	+0.11
0.65	+0.23	+0.57	+0.08	+0.11
0.70	+1.00	+0.54	+0.15	+0.13
0.75	+0.35	+0.14	+0.07	+0.09
0.80	+0.04	+0.02	+0.58	+0.03
0.85	+0.52	+0.60	-0.14	+0.04

The hybrid is ahead at every index before filtering. After filtering it is behind only at $M = 0.85$, by 0.14 and 0.04 points.

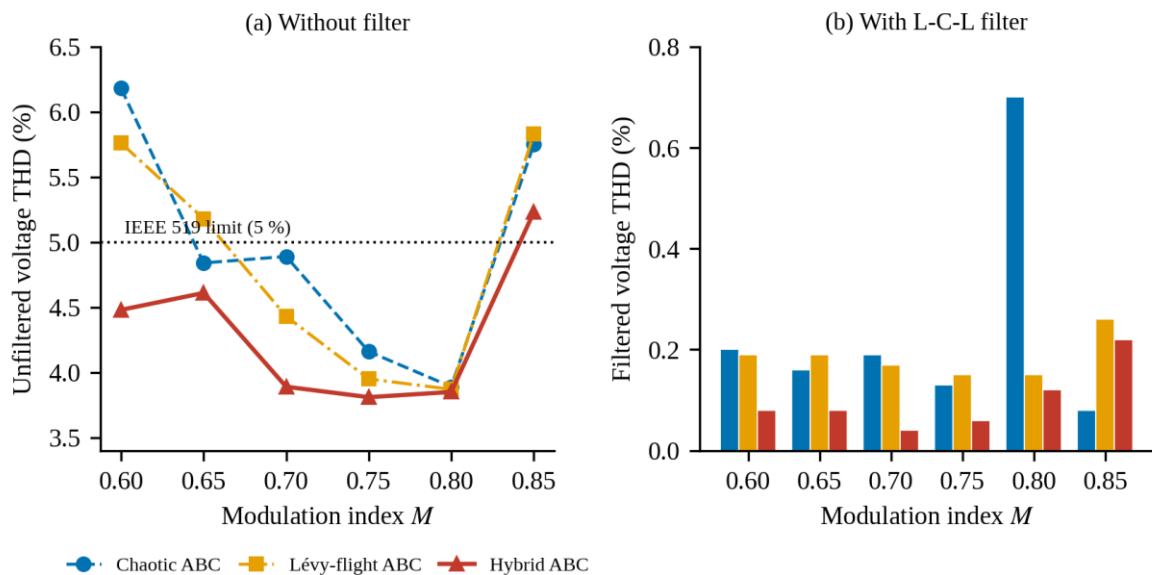


Fig. 3. Voltage THD versus modulation index for the three ABC variants. (a) Unfiltered THD with the 5 % IEEE 519 limit. (b) THD after the L-C-L filter.

6.2 Compliance and modulation-index dependence

Before filtering, the chaotic ABC exceeded the 5 % limit at two modulation indices (0.60 and 0.85), the Lévy-flight ABC at three (0.60, 0.65 and 0.85), and the hybrid at one (0.85, at 5.23 %). Table 5 collects these figures. For all three algorithms THD is non-monotonic in M : it is lowest around $M = 0.70$ –0.80 and rises at both ends. At $M = 0.85$ the hybrid spectrum is dominated by the 3rd harmonic, at about 4.1 % of the fundamental, which accounts for most of its 5.23 % THD and suggests that the available angle set cannot cancel low-order terms well near the top of the range. A stronger weighting of the 3rd and 5th harmonics in Eq. (5), or an explicit constraint on them, is a natural remedy at high M .

Table 5. Summary of harmonic performance over the six modulation indices.

Metric	Chaotic ABC	Lévy-flight ABC	Hybrid ABC
Mean unfiltered THD (%)	4.95	4.84	4.31
Unfiltered THD range (%)	3.89–6.18	3.87–5.83	3.81–5.23
M with unfiltered THD > 5 %	0.60, 0.85	0.60, 0.65, 0.85	0.85
Compliant before filtering	4 of 6	3 of 6	5 of 6

Metric	Chaotic ABC	Lévy-flight ABC	Hybrid ABC
Mean filtered THD (%)	0.24	0.19	0.10
Maximum filtered THD (%)	0.70 ($M = 0.80$)	0.26 ($M = 0.85$)	0.22 ($M = 0.85$)
Fundamental, unfiltered (V)	198.5–233.8	201.5–240.2	191.4–239.4

6.3 Effect of the L-C-L filter and fundamental voltage

The L-C-L filter reduced THD to 0.70 % or less for every algorithm at every modulation index (Fig. 3b). The hybrid gave the lowest filtered value at five of the six indices, with a mean of 0.10 % (range 0.04–0.22 %), roughly 59 % and 46 % below the chaotic and Lévy-flight means. The exception is $M = 0.85$, where the chaotic result (0.08 %) beats the hybrid (0.22 %). The chaotic value of 0.70 % at $M = 0.80$ is an isolated outlier relative to its other five points (0.08–0.20 %). Because the filter is so effective, the practical consequence of a better angle set is mainly a larger safety margin and a lighter filter requirement, not a change in whether the limit is met. The filter also raised the fundamental by about 5–6.5 V in the cases where both values were recorded.

The unfiltered fundamental rose with M for all three algorithms (Fig. 4a), from 191.4 V (hybrid, $M = 0.60$) to 240.2 V (Lévy-flight, $M = 0.85$). At low M the hybrid delivered a lower fundamental than the standalone variants, for example 191.4 V against about 199–202 V at $M = 0.60$. Its lower THD at that point therefore comes with a modest sacrifice of output voltage, which should be weighed in applications where voltage regulation matters.

6.4 Convergence behaviour

Table 6 and Fig. 4b summarise the ten-run convergence results. Within their equal 100-iteration budget, the chaotic ABC reached lower final fitness than the Lévy-flight ABC (best about 0.090 against 0.231; typical range 0.11–0.30 against 0.27–0.46), consistent with chaos favouring fast local refinement and Lévy flights spending a short budget on wide exploration. Each standalone algorithm had a weak run (0.626 and 0.923). The hybrid, run for 100 iterations, ended with final fitness between 4.39×10^{-2} and 9.89×10^{-2} in nine of ten runs, with most of the reduction achieved within the first 10–50 iterations. Run 4 stagnated near 8.05×10^{-1} , probably because of an unfavourable initial chaotic seed.

Table 6. Convergence summary over ten independent runs (final best fitness).

Algorithm	Iterations	Best run	Worst run	Typical range
Chaotic ABC	100	≈ 0.090	≈ 0.626	≈ 0.11 – 0.30
Lévy-flight ABC	100	0.231	0.923	≈ 0.27 – 0.46
Hybrid ABC	100	4.39×10^{-2}	8.05×10^{-1}	4.39×10^{-2} – 9.89×10^{-2} (9 of 10 runs)

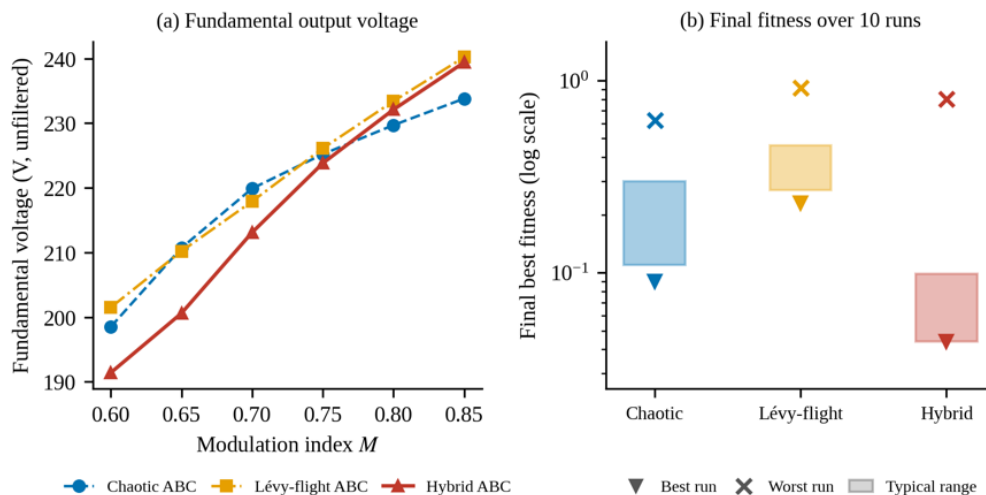


Fig. 4. (a) Unfiltered fundamental output voltage versus modulation index. (b) Final best fitness over ten runs for each algorithm (log scale); boxes span the typical range; triangles mark the best run and crosses the worst run.

6.5 Topology efficiency

All three algorithms drove the same five-bridge asymmetric inverter, which synthesised the 31 levels with 20 switches. A symmetric design with equal sources would need 15 bridges and about 60 switches, with correspondingly more gate drivers and DC sources. This saving is a property of the topology and is independent of the optimizer, but it is what makes a 15-angle SHE solution practical to implement, and it is consistent with the component-count advantage of asymmetric MLIs reported in the literature [2, 5].

6.6 Comparison with the literature

The hybrid's 10.9–12.9 % reduction in mean unfiltered THD over its standalone constituents lies within the 10–20 % improvement reported for an ABC–firefly hybrid on a 21-level inverter [18]. The present study adds a six-point modulation sweep, an explicit filter stage and ten-run convergence statistics on a 31-level inverter. The 4.31 % mean unfiltered THD is below the 4.86 % reported for plain ABC on a 15-level PV inverter [19], although the topologies and operating points differ, so the comparison is indicative only. The 2.30 % reported for BBO on a 31-level inverter [22] is lower than our unfiltered mean; the hybrid ABC instead gives consistently low THD across a range of M , and the filter then brings every tested case far below 5 %. Faster convergence reported for chaotic ABC [15] and improved diversity from Lévy flights [16] are both echoed here: the chaotic variant converged to lower fitness than the Lévy variant within 100 iterations, while the Lévy variant achieved a marginally lower mean unfiltered THD (4.84 % versus 4.95 %).

7. Conclusion

This paper compared chaotic, Lévy-flight and hybrid chaotic–Lévy ABC algorithms for selective harmonic elimination in a 31-level, five-bridge asymmetric cascaded H-bridge inverter. The hybrid delivered the lowest unfiltered THD at all six modulation indices (mean 4.31 %), the fewest violations of the 5 % IEEE 519-2022 limit before filtering (one of six, against two and three for the standalone variants), the lowest mean filtered THD (0.10 %), and final fitness clustered tightly in nine of ten runs. All three algorithms reached 0.70 % or less once an L-C-L filter was applied. The benefit of the hybrid was largest at low modulation index and nearly vanished around $M = 0.75$ – 0.80 , and all variants degraded at $M = 0.85$. The asymmetric topology realised the 31 levels with 20 switches instead of about 60.

These findings support, but do not yet prove, that combining chaotic refinement with Lévy-flight exploration is better than either alone, because the hybrid was run for far more iterations than the standalone variants. Future work should (i) repeat the comparison under equal budgets and add statistical tests, (ii) improve seed initialisation or add adaptive restarts to remove stagnating runs, (iii) strengthen the objective at high modulation index, (iv) include dead time, switching losses and DC-source imbalance, (v) benchmark against other recent hybrids, and (vi) validate on a hardware prototype.

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