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Selective Harmonic Elimination: A Comparative Analysis for Three-Phase Cascaded H-bridge Nine-Level Inverter

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Abstract: The Selective Harmonic Elimination (SHE) strategies are used for Three-Phase Cascade H-bridge Nine-Level Inverter (CHBMLI) is thoroughly investigated and compared in the present study. In order to achieve desired harmonic elimination in the CHBMLI, the study validates its effectiveness with various optimization algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Grasshopper Optimization Algorithm (GOA), and Grey Wolf Optimization Algorithm (GWO). According to the findings of the current study, it is found that PSO routinely shown the superiority over GA, GOA, and GWO in terms of voltage waveform accuracy and THD reduction. In addition to this the PSO exhibits competitive computing efficiency, making it a viable choice to improve CHBMLI system performance with reduced harmonic distortions.

Keywords: *Cascaded Multilevel Inverter, Genetic Algorithm, Pulse width modulation, Selective Harmonic Elimination.*

1. Introduction

The emergence of multilevel inverters (MLIs) makes them more popular due to their advantages in the conversion of electrical power. The major advantages in comparison to conventional inverters, they achieve lower switching losses, lower harmonics, and improved efficiency by using PWM techniques on various MLI topologies [1]. Diode-clamped, flying capacitor, and cascaded H-bridge are the three primary forms of MLI [2]. To control output voltage there is a scope to use more efficient modulation techniques.

In Modulation strategies there are two types of inverters switching methods [3]: high switching and low switching. The phase-shift, high THD, and large switching losses make the high switching modulation technique unsuitable for high-power MLIs [4]. Low-switching modulation, like SHEPWM [3-6], has been considered to be more effective because it provides effective harmonic reduction with minimal losses.

A Selective Harmonic Elimination (SHE) modulation technique aims to eliminate particular harmonics from an output voltage waveform thereby quality of the output would be better. This is accomplished by using a well specified switching pattern. The optimization procedure is used to select the switching angles with the goal of reducing the total harmonic distortion (THD) in the output voltages.

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The mathematical problems connected to SHE can be solved using a variety of techniques, and research is still being done to improve these techniques. Numerical methods, algebraic techniques, and algorithms based on evolutionary computation can all be used to solve SHE equations. Inaccurate numerical techniques, such as the Newton-Raphson method stated in [5, 6], may converge to poor solutions because of local optima. These techniques frequently have low throughput, slow convergence, great computing complexity and limited accuracy.

Recent research has concentrated on the application of clever optimization methods to accomplish effective harmonic removal in multilevel inverters in order to get around these restrictions [8]. Particle swarm optimization (PSO), Ant Colony Optimization (ACO), Genetic Algorithm (GA), Artificial Bee Colony (ABC) Algorithm, Differential Evolution (DE), Harmony Search (HS) Algorithm, Grey Wolf Optimization (GWO) and Grasshopper Optimization Algorithm (GOA) are a few of the algorithms that have demonstrated promising results in a variety of applications [7, 8].

This paper analyzes and compares the GA, PSO, GOA, and GWO algorithms for selective harmonic elimination in a three-phase, nine-level CHBMLI. The goal of this study is to evaluate these optimization algorithms' computational efficiency, and accuracy in identifying the best switching angles for harmonic elimination in the nine-level inverter.

In the rest of the paper, Section 2 provides a brief overview of the nine-level inverter topology and its operating principles. Section 3 discusses the mathematical formulation of the selective harmonic elimination problem. Section 4 presents the detailed methodology for each optimization algorithm. Section 5 presents and analyses the simulation results obtained from nine-level CHBMLI using the GA, PSO, GOA and GWO algorithms. Finally, Section 6 concludes the paper and provides insights into future research directions.

2. Cascaded Multilevel Inverter

The three-phase multilevel converter is composed of a series of 3-phase H-bridge inverters. These inverters are connected in such a way that they produce a sinusoidal wave voltage. Each cell of the inverter is supplied by a DC source, and it is associated with a cascade 3-leg 3-phase inverter. The output of the multilevel converter has 2n+1 levels, with 'n' being the number of cells [2], [8]. The adjustment of the switching angles helps optimize the THD. The multilevel converters require fewer components than traditional diode clamped and flying capacitor converters, making them more cost-effective. Fig. 1(a) presents us with a three-phase, nine-level cascade H-bridge Inverter. In comparison to neutral point clamped inverter (NPC), its control structure exhibits greater performance [7]. This inverter features nine levels, similar to other inverters, and is composed of four H-bridge inverters connected as a one lag cascade. It has been constructed using 16 switching devices [9]. Fig. 1(b) shows the 9-level cascaded H-Bridge inverter waveforms.

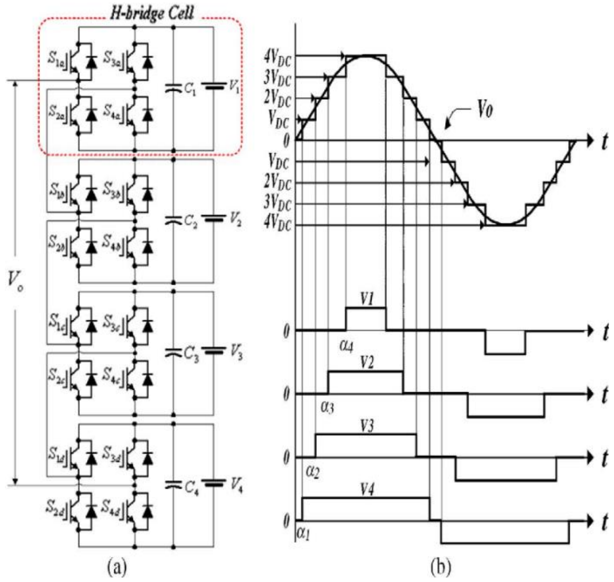


Fig. 1. (a) Cascaded H-Bridge of multilevel inverter 3-phase nine-level, (b) Staircase output voltage waveform of nine-level inverter

3. Selective Harmonic Elimination Pulse Width Modulation

Fourier series analysis of the phase voltage of a three-phase CHBMLI is used to establish the SHE equations for this device. Due to the odd nature of the function and the assumption of quarter-wave symmetry and equal amplitudes for DC sources, even harmonics and cosine components become zero, resulting to a particular Fourier series expansion [8], [9].

$$v(t) = \sum_{n=1}^{\infty} An \sin(n\omega t)$$

(1)

Where, An is the amplitude of the harmonics and α is the angle between zero and 90° (0 ≤ α ≤ 90). The harmonics of an even order become zero because of the quarter-wave symmetric property, which results in:

$$A_n = \begin{cases} \frac{4Vdc}{\pi} \sum_{i=1}^{s} \frac{\cos(n\alpha i)}{n} & n: \mathrm{ODD} \\ 0 & n: \mathrm{EVEN} \end{cases} \tag{2}$$

Equation (2) is used to find harmonic orders, in a three-phase system, the even-order harmonics and triplet harmonics are equal to zero. Only the non-triple odd harmonics (5th, 7th, and 11th) of the phase voltage waveform must be reduced in a nine –level inverter. In other terms, the following equation must be resolved for a 9-level inverter:

$$cos(\alpha 1) + cos(\alpha 2) + cos(\alpha 3) + cos(\alpha 4) = 4MI = ma \tag{3}$$

$$\begin{aligned} cos(5\alpha 1) + cos(5\alpha 2) + cos(5\alpha 3) + cos(5\alpha 4) &= 0 \\ cos(7\alpha 1) + cos(7\alpha 2) + cos(7\alpha 3) + cos(7\alpha 4) &= 0 \\ cos(11\alpha 1) + cos(11\alpha 2) + cos(11\alpha 3) + \cos(\alpha 4) &= 0 \end{aligned} \tag{4}$$

Equation 3 represents the fundamental component in terms of modulation index, while Equations 4 represent equations for harmonics to be eliminated.

Where ma is the modulation index (MI), the ma is expressed as:

$$ma = \frac{V_1}{\frac{4VdcS}{\pi}} \tag{5}$$

Where S is the number of different DC sources, V_1 is the intended fundamental voltage, and V1max is the maximum fundamental voltage. The maximum value of the CHMLI output voltage level is equal to the symmetrical DC source voltage (Vdc) that powers each cascaded H-bridge inverter. When switching angles α1, α2 α3 and α4 reduce to 0, a square wave with an amplitude of VdcS occurs, resulting in V1max = 4VdcS/π.

4. Optimization Algorithm

4.1. Genetic Algorithm (GA)

The common harmonic reduction issue in multilevel inverters has been successfully resolved using GA [9]. In comparison to more traditional harmonic elimination techniques, the GA-based harmonic elimination method significantly lowers the output voltage waveform's THD level and offers a number of benefits. As opposed to other traditional optimization methods, GA finds the best switching angles to minimize the harmonic content of the output voltage waveform without the use of a precise mathematical model or any presumptions. Due to the fact that the GA-based harmonic elimination is not iterative and does not rely on the outcomes of previous iterations, it can be effectively employed to address complex optimization issues. The goal of GA is to find the optimum solution that satisfies the required cost function. It does this by using the ideas of natural selection and genetic crossover. The population solution is used by fusing their genes where new solutions are produced. The fitness function is then maximized in each iteration by choosing the best solution. The fitness function is computed using equation (6) for each solution (or chromosome).

The genetic algorithm (GA) is employed in the three-phase, nine-level MLI to minimize the odd harmonics while keeping the fundamental component of the phase voltage waveform as per requirement. The fitness function is represented by the symbol FV in equation (6). The fitness function of the output voltage waveform correlates to the THD in the harmonic removal issue. In order to discover the best switching angles for multilevel inverters, the GA-based harmonic elimination method is efficient and useful. One disadvantage of using GA for efficient harmonic reduction is that it could be computationally costly. Iterations are required to get the best result with the GA number. Moreover, GAs may be sensitive to the initial conditions, which could lead to the discovery of distinct solutions for the same problem [10, 11].

$$\left\{ \begin{matrix} FV = 100 * [|\mathrm{maV1max} - \frac{|V1|}{V1max}| \\ + \sum_{n}^{\sigma} = 5,7,11 \frac{|V1|}{V1max} \end{matrix} \right\} \tag{6}$$

4.2. Particle Swarm Optimization

Particle swarm optimization (PSO) is a computational technique that draws inspiration from the collective behavior observed in bird flocking. This technique offers a viable approach for obtaining an approximate solution to a numerical optimization problem. The Particle Swarm Optimisation (PSO) algorithm uses a population of particles with a strong evolutionary direction and convergence, which is similar to how individuals work in a genetic algorithm, to find the best solutions. The population of particles is initialized randomly; the initial location of each particle is referred to as the personal best position (Pbest). The fitness value of each particle is evaluated using the fitness function. Based on the lowest fitness value, the global best (Gbest) value is selected. The particle position and their velocities are updated using the following equations (7) and (8), respectively [12-15].

The update equation for the velocity vector is:

$$\begin{aligned} Vi(t+1) = wVi(t) + c1r1\big(Pbesti(t) - Xi(t)\big) \\ + c2r2\big(Pbestg(t) - Xi(t)\big) \end{aligned} \tag{7}$$

position vector Xi is then updated based on the new velocity vector:

$$Xi(t+1) = Xi(t) + Vi(t+1) \tag{8}$$

This update process repeats until the desired solution is found.

4.3. Grasshopper Optimization Algorithm

For the purpose of resolving numerical problem optimization, the GOA algorithm is inspired by the foraging and swarming behaviour of grasshoppers in nature. In its life cycle, the grasshopper goes through two stages: nymph and adulthood. The nymph stage is distinguished by small steps and slow motions, while the adult stage is highlighted by long-distance and swift movements. The motions of nymphs and adults serve as representations of the times of GOA's intensity and diversification. The GOA search procedure can be divided into two stages as exploration and exploitation. In the exploration phase, we calculate the fitness value of each grasshopper swarm (which looks for food sources) and update all the location values. In the exploitation phase, the ideal answer has been identified (looking for superior food sources) among all possible choices. A more detailed explanation of GOA can be found in [16, 17].

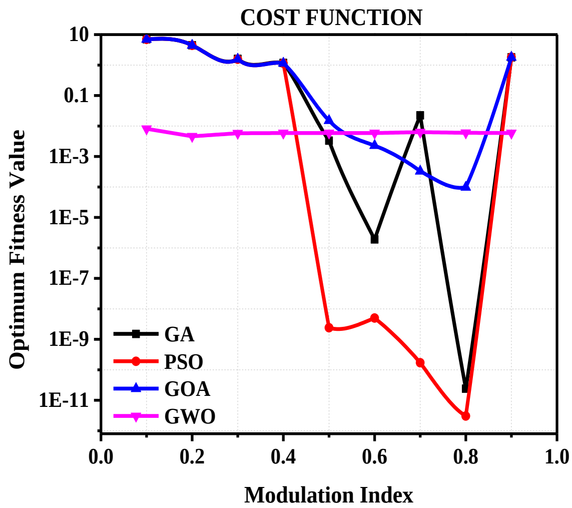
4.4. Grey Wolf Optimization

An optimization method that draws inspiration from nature and imitates the social behaviour of grey wolves is called the Grey Wolf Optimization (GWO) algorithm. It constructs a hierarchical structure out of a population of alternative solutions termed "wolves" based on their fitness. The top options available are alpha, beta, delta, and omega wolves. Following the alpha, beta, delta, and omega wolves with changing degrees of aggression allows wolves to update their places. This procedure keeps going until a termination condition is satisfied after a predetermined number of iterations. The position of the alpha wolf often represents the best answer discovered. An effective optimization solution has been achieved in many fields using GWO.A multilevel inverter system's switching patterns can be optimized using the Grey Wolf Optimization (GWO) algorithm to boost efficiency. A fitness function that measures the inverter's desired output quality, such as minimizing total harmonic distortion (THD) or maximizing efficiency, is used by GWO to iteratively alter these patterns. Better-performing switching patterns have an influence on other switching patterns' updates when the algorithm arranges the switching patterns in a hierarchy. An optimized switching pattern that raises the multilevel inverter's performance in line with the stated goals is the end result of this process, which is continued until a termination condition is met. A more detailed explanation about GWO can be found in [18-20].

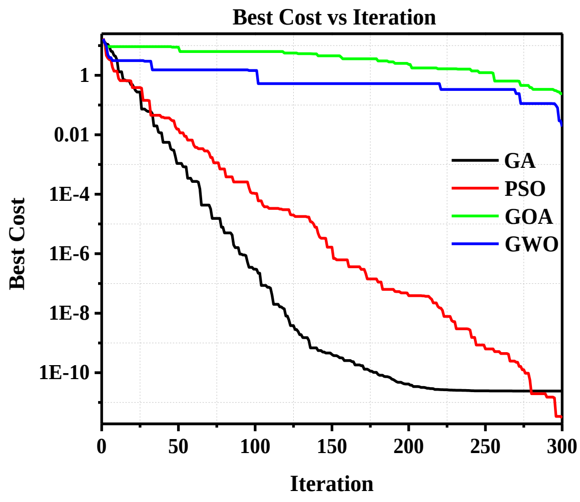
5. Results and Discussion

For analyzing the performance of the proposed inverter, the simulation studies have been carried out using MATLAB/Simulink with four 80-V identical DC supplies with fundamental frequency 50Hz operating with purely resistive load of 10 Ω, Considering the lower and higher boundary limits of 0° and 90°, respectively. The suggested SHE-PWM technique has been implemented using MATLAB (R2020a).

The ideal fitness value and the associated modulation index were found using four optimization techniques such as GA, PSO, GOA, and GWO, and the results derived from each implementation are shown in the form of a graph in Figure 2(a). It was found that PSO yield the lowest fitness value at MI=0.8 as compared to the other three processes. The rate of convergence for PSO is also found to be better than that of GA, GOA, and GWO techniques, as shown in Figure 2(b).

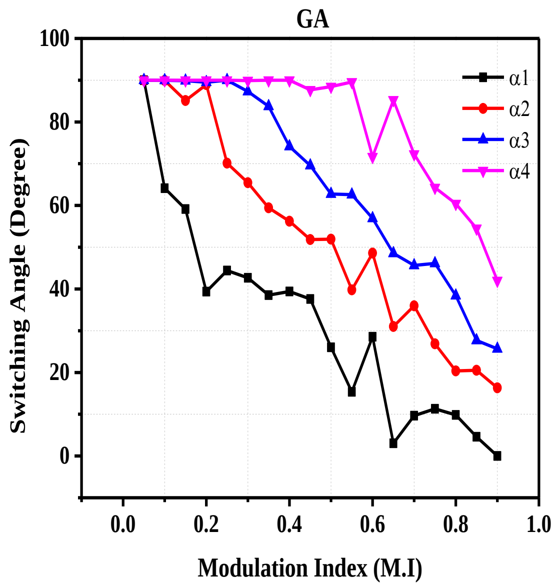


(a) Optimum fitness value with respect to modulation index

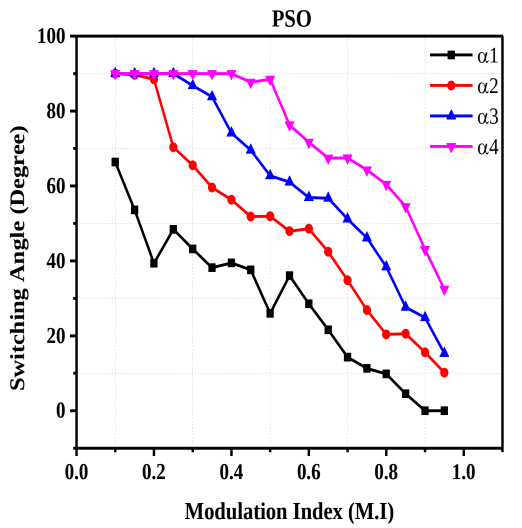


(b) Rate of convergence

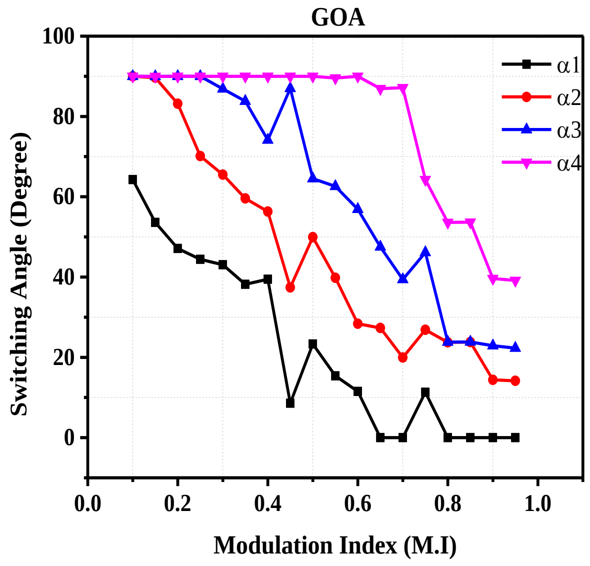
Fig. 2. Comparative analysis between GA, PSO, GOA and GWO



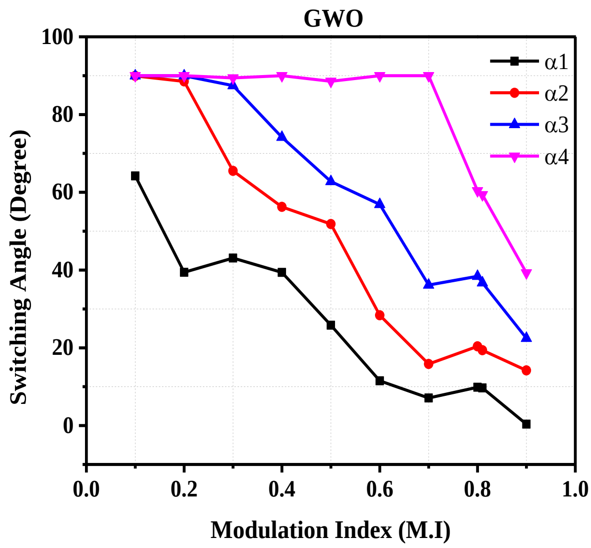
(a) GA



(b) PSO



(c) GOA



(d) GWO

Fig. 3. Optimum switching angles with respect to the modulation index for (a) GA, (b) PSO, (c) GOA and (d) GWO

Figure 3 shows the best switching angles determined for four distinct switching algorithms (GA, PSO, GOA, and GWO) for various modulation indexes. The nine-level multilevel inverter uses this computed switching angle to perform the switching at various modulation indexes to produce an output voltage with the desired number of voltage levels.

Table 1 summarizes the comparative analysis in detail with proposed GA, PSO, GOA, and GWO based SHEPWM CHBMLI of Simulink model at different modulation indexes. The results of GA, PSO, GOA, and GWO are highlighted with the advantages of their own based on different criteria like computation time (tc), cost function, voltages and THD. From the comparison, it is observed that:

1. As compared to GA, PSO and GOA, the GWO algorithm's computation time (tc) is very small. Additionally, it has been noted that the tc of PSO algorithm's is lower than that of GA and GOA.

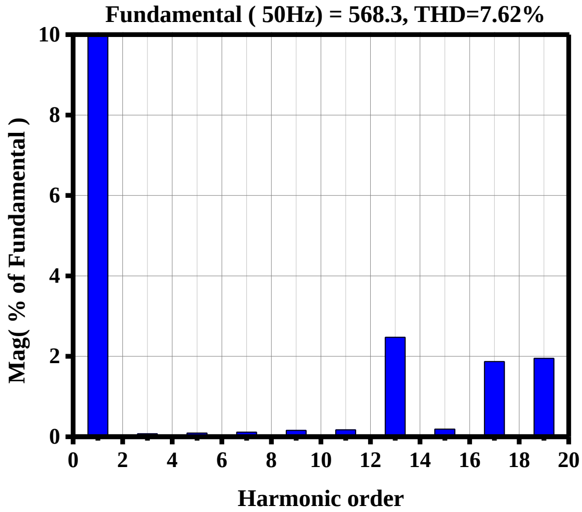
2. The PSO algorithm's cost function is the lowest when compared to GA, GOA, and GWO. It is also noted that, among the four optimization procedures, the quantity of THD obtained is also lowest when the modulation index (M.I.) is equal to 0.8. Additionally, when MI=0.8, GWO's THD value is lower than that of GA, GWO, and PSO (GWO's line voltage THD is 6.69%, PSO's is 7.09%, GA's is 7.62%, and GOA's is 6.85%). Figure 4 shows the line voltage FFT analysis graphs obtained at MI=0.8 of 9-level CHB-MLI for GA, PSO, GOA, the GWO algorithms. Figure 5 shows the THD variations versus modulation indexes of 9-level CHB-MLI for GA, PSO, GOA, the GWO algorithms.

3. When MI=0.8, the Phase and Line voltages are essentially identical in all cases to their expected values (the Phase voltage is 230V and the Line voltage is 400 V). In contrast to the GA, GOA, GWO, and PSO algorithms, the phase voltage is 230.3V and the line voltage is 399.8V, which clearly demonstrating that the achieved value is almost similar to the specified value, i.e., the line voltage is equal to the 3-Phase Voltage.

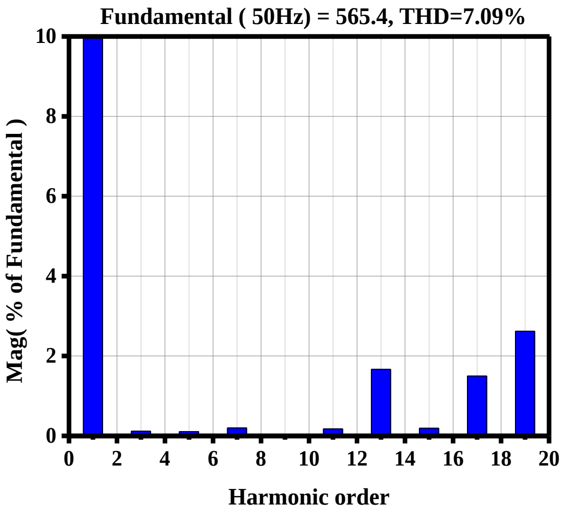
Overall, the cost function of the PSO algorithm is the least, which stands out in achieving the best outcomes, despite the fact that the tc and THD values of the PSO method are somewhat greater than those of the GWO algorithm. This issue can be minimized by the hybridization of different optimization algorithms.

Table 1. Comparison of GA, PSO, GOA and GWO based SHEPWM CHBMLI

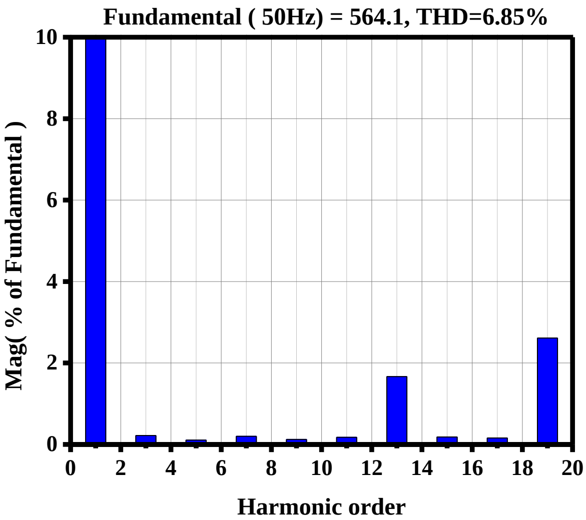
Optimization algorithm	M.I	tc,s	Cost function	Lower order harmonics			RMS Voltage(V)		%THD	
				5th	7th	11th	Phase	Line	Phase	Line
GA	0.1	2.0647	6.9886	0.783	0	0	47.96	64.2	106.39	58.76
	0.2	2.4972	4.4434	0	0	0	65.43	105.6	49.51	32.75
	0.3	2.214	1.589	0	0	0	100.84	153.4	54.95	21.46
	0.4	2.2537	1.17E+00	0	0	0	130.9	203.9	48.67	14.38
	0.5	2.2868	3.30E-03	0	0	1.2506	156.8	251.1	42.89	11.03
	0.6	2.0263	1.90E-06	0	0	1.1022	187.7	303.3	37.13	8.88
	0.7	2.68	0.0224	0	0	0	204	350.3	16.85	9.07
	0.8	1.8761	2.41e-11	0	0	0	232.3	401.8	10.62	7.62
	0.9	1.9205	1.7858	0	0	0.0539	262.3	450.7	14.91	7.38
PSO	0.1	0.41667	6.972	0.7818	0	0	46.61	61.92	113.61	66.86
	0.2	0.44058	4.437	0	0	0	65.2	105.3	49.51	31.57
	0.3	0.45383	1.5534	0.3107	0	0	99.84	153.9	54.95	21.64
	0.4	0.44449	1.1461	0.2292	0	0	128.9	201.9	48.67	14.38
	0.5	0.43319	2.4E-09	0	0	1.8701	152.1	251.6	33.29	12.86
	0.6	0.44449	5E-09	0	0	1.1022	184.7	301.1	37.13	8.88
	0.7	0.43678	1.7E-10	0	0	0	206.1	350.9	18.9	7.72
	0.8	0.41793	3.04e-12	0	0	0	230.3	399.8	9.98	7.09
	0.9	0.41965	1.811	0	0.1987	0	262.4	450.3	15.13	7.28
GOA	0.1	22.1413	6.9726	0.78292	0.00012	0	47.96	64.2	106.4	58.76
	0.2	30.1562	4.437	0	0	0	65.43	105.7	64.95	31.57
	0.3	34.7214	1.5597	0.29116	0.01253	0	99.84	153.9	54.96	21.65
	0.4	39.4285	1.1461	0.22736	0	0	128.9	201.9	48.73	14.2
	0.5	31.0315	0.015078	0	0	1.0935	152.1	251.3	33.28	12.5
	0.6	31.5033	0.0022838	0	0	1.0991	174	299.9	13.86	8.637
	0.7	26.4474	0.00032958	0	0	0	204.6	350.9	16.86	9.804
	0.8	20.1776	9.76E-05	0	0	0	230.1	398.87	9.651	6.85
	0.9	24.0901	1.7813	0	0.04274	0	262.2	450.1	14.76	7.168
GWO	0.1	7.0199	0.0081	0.7856	0	0.9536	46.46	78.28	106.39	58.76
	0.2	4.4443	0.0046	0	0	0	82.93	141.9	49.51	31.78
	0.3	1.537	0.0058	0.3003	0	0.0112	122.1	211.3	54.17	22.13
	0.4	1.1648	0.0059	0.2224	0	0	163.9	282.6	48.67	14.38
	0.5	0.11562	0.0059	0	0.0088	0	204.1	352.6	33.29	12.57
	0.6	0.1549	0.0059	0	0	0.0035	173.24	424.8	12.83	9.08
	0.7	0.97117	0.0063	0.0019	0	0.0021	198.68	344.36	17.97	6.80
	0.8	0.029783	0.0060	0	0	0	231.3	399.09	9.64	6.69
	0.9	1.7608	0.0059	0	0.0012	0	263.75	456	17.25	6.83



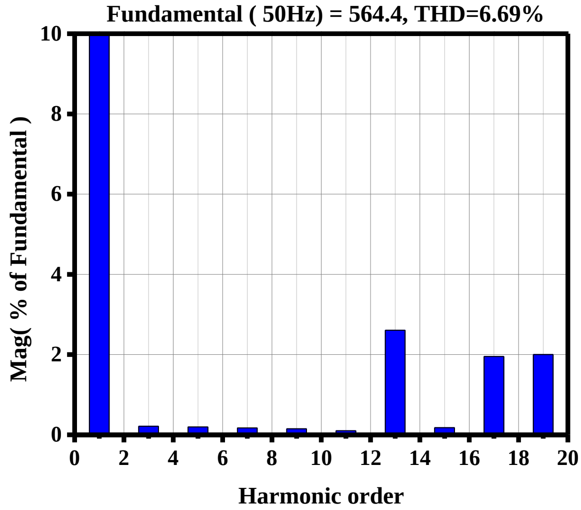
(a) GA



(b) PSO



(c) GOA



(d) GWO

Fig. 4. Line voltage FFT Analysis Graphs obtained at MI=0.8 of 9-level CHB-MLI for GA, PSO and GOA, the GWO algorithm's

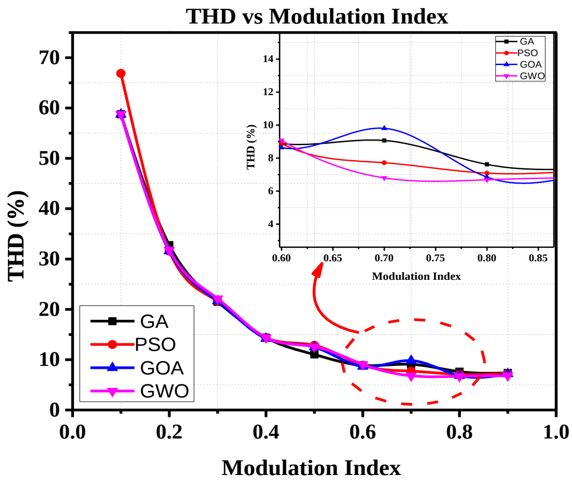


Fig. 5. THD variations verses modulation indexes of 9-level CHB-MLI for GA, PSO, GOA, the GWO algorithm's

6. Conclusion

The current study demonstrates the detailed investigation and comparison of the GA, PSO, GOA, and GWO within the SHEPWM settings for Three-Phase Nine-Level CHEMLI. New perspectives on the efficiency and functionality of the GA, PSO, GOA, and GWO algorithms are offered by the findings, which offer significant guidance. Overall, while requiring a little more computation time and having slightly higher THD values than GWO, the PSO approach outperforms it. Due to its ability to deliver extremely exact voltage values, especially when M.I. is 0.8, it is a fantastic contender for this specific optimization job. For researchers and practitioners seeking the best compromise between computing time, THD, and cost function optimization, the PSO approach is a feasible option.

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Author contributions

The first author bears the responsibility for various aspects of the paper, including conceptualization, methodology, model development, validation, investigation, preparation of the initial manuscript, and visualization of the results. The administration of the writing endeavour was supervised, reviewed, and edited by the second author.

Conflicts of interest

The authors declare no conflict of interest.

References

[1] Rodriguez, J.; Lai, J.; Peng, F.Z. “Multilevel inverters: A survey of topologies, controls, and applications”. IEEE Trans. Ind. Electron. 2002, 49, 724–738.

[2] Noman, A., Al-Shamma’a, A.A., Addoweesh, K., Alabduljabbar, A., Alolah, A. "Cascaded multilevel inverter topology based on cascaded H-bridge multilevel inverter" . Energies 11(4), 895 (2018).

[3] Ezhilarasan, G., K. Mohanraj, Pradeep Vishnuram, Mohit Bajaj, Vojtech Blazek, Lukas Prokop, and Stanislav Misak. "An empirical survey of topologies, evolution, and current developments in multilevel inverters." Alexandria Engineering Journal 83 (2023): 148-194.

[4] Jammala, Venkataramanaiah, Suresh Yellasiri, and Anup Kumar Panda. "Development of a new hybrid multilevel inverter using modified carrier SPWM switching strategy." IEEE Transactions on Power Electronics 33, no. 10 (2018): 8192-8197.

[5] Dahidah, Mohamed SA, and Vassilios G. Agelidis. "Selective harmonic elimination PWM control for cascaded multilevel voltage source converters: A generalized formula." IEEE Transactions on power electronics 23, no. 4 (2008): 1620-1630.

[6] Bousmaha, Imen Souhila, Seyf Eddine Bechekir, Djaffar Ould Abdeslam, Marref Mohammed Amine, Mokhtaria Jbilou, and Mostefa Brahami. "SHEPWM in three-phase voltage source inverters by modified Newton–Raphson." International Journal of Power Electronics and Drive Systems 14, no. 1 (2023): 25.

[7] De León-Aldaco, Susana Estefany, Hugo Calleja, and Jesús Aguayo Alquicira. "Metaheuristic optimization methods applied to power converters: A review." IEEE Transactions on Power Electronics 30, no. 12 (2015): 6791-6803.

[8] Ritu Saxena, Dr. H.K. Verma, Dr. Arun Parakh, Mrs. Rinki Rajpal, “Harmonic Reduction of Multilevel Inverters by Using Soft Computing Techniques: A Review”, 3rd International Conference on Sustainable and Innovative Solutions for Current Challenges in Engineering & Technology (ICSISCET 2021).DOI: https://doi.org/10.52458/978-93-91842-08-6-40

[9] Urgun, Satilmis, and Halil Yigit. "Selective harmonic eliminated Pulse Width modulation (SHE-PWM) method using genetic algorithm in single-phase multilevel inverters." International Journal on Electrical Engineering and Informatics 13, no. 1 (2021): 191-202.

[10] B. Ozpineci, L. M. Tolbert, and J. N. Chiasson, “Harmonic optimization of multilevel converters using genetic algorithms,” IEEE Power Electronics Letters, vol. 3, no. 3, pp. 92–95, 2005.

[11] Chatterjee, Shantanu, and Abhijit Das. "A review on technological aspects of different PWM techniques and its comparison based on different performance parameters." International Journal of Circuit Theory and Applications 51, no. 5 (2023): 2446-2498.

[12] Gad, Ahmed G. "Particle swarm optimization algorithm and its applications: a systematic review." Archives of computational methods in engineering 29, no. 5 (2022): 2531-2561.

[13] Sadoughi, Milad, Amirhossein Pourdadashnia, Mohammad Farhadi-Kangarlu, and Sadjad Galvani. "PSO-optimized SHE-PWM technique in a cascaded H-bridge multilevel inverter for variable output voltage applications." IEEE Transactions on Power Electronics 37, no. 7 (2022): 8065-8075.

[14] Qin, Xinxiao, Weihao Hu, Yuanhong Tang, Qi Huang, Zhe Chen, and Frede Blaabjerg. "An improved modulation method for modular multilevel converters based on particle swarm optimization." International Journal of Electrical Power & Energy Systems 151 (2023): 109136.

[15] Vishwanath, B. R., and P. S. Puttaswamy. "Performance Analysis of SHEPWM Based on GA and PSO for CMLI." In Emerging Research in Electronics, Computer Science and Technology: Proceedings of International Conference, ICERECT 2018, pp. 1311-1329. Springer Singapore, 2019.

[16] Shahrzad Saremi, Seyedali Mirjalili, Andrew Lewis, “Grasshopper Optimization Algorithm: Theory and application”, Advances in Engineering Software, Volume 105, 2017, Pages 30-47, ISSN 0965-9978, https://doi.org/10.1016/j.advengsoft.2017.01.004.

[17] Wu, L., Wu, J. & Wang, T. “Enhancing grasshopper optimization algorithm (GOA) with levy flight for

engineering applications". Sci Rep 13, 124 (2023). https://doi.org/10.1038/s41598-022-27144-4.

[18] Seyedali Mirjalili, Seyed Mohammad Mirjalili, Andrew Lewis, "Grey Wolf Optimizer, Advances in Engineering Software", Volume 69, 2014, Pages 46-61, ISSN 0965-9978, https://doi.org/10.1016/j.advengsoft.2013.12.007.

[19] M. H. Arshad, B. Ismail, M. Z. Aihsan, W. A. Mustafa, H. A. Rahim and A. S. A. Sinnee, "Harmonic Analysis of Modified Nine-level Inverter with SHEPWM using Grey Wolf Optimization," 2021 4th International Iraqi Conference on Engineering Technology and Their Applications (IICETA), Najaf, Iraq, 2021, pp. 123-129, doi: 10.1109/IICETA51758.2021.9721.

[20] Fei, He, and Jiabei Shen. "Harmonic Elimination in Inverter Using Modified GWO Algorithm Check for updates." In The proceedings of the 10th Frontier Academic Forum of Electrical Engineering (FAFEE2022): Volume II, vol. 1054, p. 165. Springer Nature, 2023.