Electromagnetic Field Optimization Based Selective Harmonic Elimination in a Cascaded Symmetric H-Bridge Inverter

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Abstract: Multilevel inverters (MLIs), both symmetrical and asymmetrical, have shown to be useful in a number of applications. Continuous improvements in output voltage waveform control and converter size reduction have made this practicable. The output voltage is managed using a low frequency modulation technique called selective harmonic elimination. This paper investigates an unique selective harmonic elimination (SHE) control that uses electromagnetic field optimization (EFO). The major features of the EFO guarantee that the targeted harmonics are removed via computation of the ideal angles, such as its easier compilation procedure and capacity for single-stage local and global searches. Additionally, a comparison with well-known algorithms namely Genetic Algorithm and Differential Evolution in accessing performance based on Total Harmonic Distortion demonstrates the EFO's competence. The suggested algorithm’s performance has been tested using a symmetric cascaded H-Bridge MLI structure. In the MATLAB/Simulink environment, simulation analysis is performed, validating the viability of the created system. To further show the effectiveness of the suggested approach, experimental testing using low switching frequency control methods has been carried out in a dynamic setting.

Keywords: multilevel inverter; selective harmonic elimination; electromagnetic field optimization (EFO)

1. Introduction

Due to its flexibility to function in a wide variety of applications, Multilevel inverters (MLIs) are outpacing traditional inverters [1–5]. The main drivers behind the phenomenal development and deployment of MLIs in renewable power application, electrical vehicles, power transmission and industrial applications are enhanced interference compatibility, reduced stress on switches, lower switching and conduction losses, and improved power quality [3–7]. Depending on the quantity of dc supply, power electronic switches, and capacitors utilized, MLIs may provide output that looks like a staircase sinusoidal wave. Diode-clamped MLI (DMLI), flying capacitor MLI (FMLI), and cascaded H-bridge MLI (CMLI) are three popular traditional MLI topologies [2,8–10]. The main issues with DMLIs and FMLIs are voltage balancing, the need for clamping diodes/capacitors, and susceptibility to module failure owing to series connection of switches.

Due to its adaptability and dependability qualities, multi-dc CMLIs are attracting a lot more attention than these single dc MLIs. Additionally, whereas asymmetric topologies may greatly increase the number of levels using the same amount of components, symmetrical CMLIs are easier to govern [11].

However, a significant drawback of the conventional MLIs is the need for additional semiconductor switches and dc sources. Continuous study has been conducted in recent years to find the best ways to improve the MLI structure. Three different types of MLIs—switched-dc MLI, switched-capacitor MLI, and switched-diode MLIs (SMLIs)—are studied [12]. A switched-dc symmetrical structure with fewer switches than the traditional architectures has been suggested in [13]. Although this topology does not need a back-end H-bridge to change the polarity, it still needs isolated sources that are the same as the CMLI.
to synthesize any voltage level. Structures suggested in [14,15] are likewise competitive and economical in the switched-dc category. These simplified switch designs may naturally flip voltage polarity, and by cascading the fundamental units, greater voltage steps can be achieved. The best architectures are described in [16,17] and use the H-bridge incorporated into the fundamental units to generate 15 levels utilizing 16 switches and 7 isolated DC sources. Additionally, there is a potential of expansion to create any voltage levels using various dc source amplitudes and with less voltage stress on the switches. Asymmetrical and symmetrical MLIs with various pulse width modulation (PWM) control schemes have also been introduced in [18] and [19], respectively, based on the aforementioned principle. Switched-dc compact module topologies have been examined in [20–22] as a potential substitute for the traditional MLIs.

As was already noted, the MLIs lower the switch count but do not have voltage boosting capabilities. In order to increase voltage levels without adding more transformers and inductors, switched-capacitor topologies have been devised [23]. The configurations shown in [24,25] significantly decrease the number of semiconducting devices while simultaneously having the potential to enhance voltage using the same basic unit. More recently, in [26,27], extended switched-capacitor topologies with low costs, few dc sources, and lower total standing voltage (TSV) have been suggested. These architectures also have the benefit of self-regulating capacitor voltage utilizing the series-parallel charge-discharge method.

The number of driving circuits grows as more switches are used, which in turn raises control complexity. The development of the switched-diode structures was driven by the need to simplify the circuit. Circuit topologies shown in [28–30] need a much less complicated control. These architectures call for fewer switches and lower power loss for five-level and seven-level activities. The inclusion of diodes in the direction of the reverse current flow makes these switched-diode designs appropriate for high power factor loads, however, for low power factor loads, loading spikes in the output voltage may arise. For many applications, a workable trade-off between circuit simplicity and load handling capacity is consequently essential. In addition to the design challenges mentioned above, implementing a proper control method for MLI is a significant obstacle to enhancing voltage and current quality [11,31].

The selective harmonic elimination (SHE) control approach based on fundamental frequency is commonly used in place of carrier-based PWM techniques to efficiently minimize switching power losses and totally remove the prominent harmonic components [19,22,32–34]. In SHE control, the fundamental level is kept constant while the targeted harmonics are removed using the predetermined angles. When using SHE, the following methods are used to establish the SHE angles that correspond to the lower order harmonics in question whose elimination is desired.

1. The algebraically challenging approaches;
2. The numerical methods where convergence depends on proper selection of initial solution; and
3. The simple-to-implement evolutionary algorithms, which are less reliant on early conditions [35]. The total harmonic distortion (THD) of current or voltage of the inverter is typically used in the literature as a measure for assessing the effectiveness of the SHE technique in [36] and [37]. Because the analytical methods have not been sufficiently competitive, metaheuristic approach is used as resilience procedures to obtain angles for SHE in the complete range of modulation index [35–39]. This is crucial because M values vary over a broader range when power electronic inverters used in drives application are required to function over a range of torque and speed [38,39]. In [37], a thorough analysis of SHE for resolving the inverter’s harmonic removal problem with a focus on nine well-known metaheuristic optimization techniques is offered. All of these algorithms have been discovered to be simple to use and to have a great deal of potential for resolving the harmonic removal issue in inverters. The coordination among two search schemas, exploration (diversification) and exploitation, is what gives metaheuristic algorithms their powerful search mechanism (intensification).
Numerous numerical iterative algorithm-based methods to determine the best angles have been tested in [10,19,29]. The literature demonstrates the resilience of these methods when considering real-world switching operations, unbalanced sources, the reachability of solutions across a wide modulation range, etc. By keeping a certain goal in mind, harmonic equations are solved to get the best angles. In the literature, methodologies based on numerical calculations have been further examined. Majority of engineering problems nowadays, are being tackled by means of optimization techniques, specifically bio-inspired intelligent algorithms (BIAs) [40–44]. The key advantage associated with such algorithms is that they are not entirely reliant on initial assumptions and are also computationally less difficult. Moreover, with the help of low-cost powerful computers, BIAs are simple to learn and implement. Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bee Algorithm (BA), and Differential Evolution (DE) are some examples of BIAs [41]. An objective function is used in the BIAs which has non-linear transcendental equations of lower-order harmonics and fundamental. The objective function is reduced in this method so as to obtain optimal firing angles that eliminate undesirable harmonics. The formation of an objective function has a considerable impact on the BIAs performance.

Genetic Algorithm (GA) is used in the MLI for selective harmonic elimination (SHE) in [45–48]. In the case of asymmetrical MLI, though, GA is inefficient in calculating the optimized switching angles. Differential Evolution (DE) technique is introduced in [49]. Reference [21] proposes the Bee Algorithm (BA), however it is more computationally challenging than GA. The Colonial Competitive Algorithm (CCA) is described in [50]. Another algorithm called Generalized Pattern Search (GPS) is proposed in [51]. The GPS method is a direct search technique that is primarily used in small areas for local refinement. GPS algorithm also experiences problem in finding the solutions in case of high dimension problems and it is not able to find feasible solutions for such problems. This is due to the fact that GPS has limited exploration capability and therefore it stuck at local minima [52]. In [53], the performance of the most well-known and popular optimization techniques (GA, PSO, BA, DE, and CCA) for SHE in case of 7-level inverter is compared on the basis of different parameters i.e., accuracy, convergence speed, number of control parameters, and computing complexity. According to the results, the PSO algorithm outperforms the GA, BA, DE, and CCA algorithms in terms of accuracy and convergence speed. Furthermore, PSO has a lower computational complexity as compared to the GA, BA, and DE.

For asymmetrical MLI [53], the PSO algorithm is employed. Ref. [20] employs the memetic algorithm (MA). Nevertheless, if the number of firing angles is increased, MA takes a very long time to get the optimized solutions. Ref. [54] employs a PSO-NR hybrid algorithm. In [55], a species seed technique-based PSO (S-PSO) is introduced. But computational complexity increases in this technique because of the calculation of the Euclidean distance in every iteration which leads to slow convergence rate. The PSO method is presented in [56] for current and voltage harmonics removal in 3-level inverter based induction motor drives that are appropriate for traction applications. To enhance convergence speed, the Mesh Adaptive Direct Search method (MADS) is used with the PSO algorithm in [57]. A modified PSO is employed in [58] for the calculation of optimized switching angles in MLI having lesser switches. In [59], the GA and PSO are used individually to determine the optimal firing angles in case of 7-level inverter. The obtained firing angles are then given to NR as an initial guess for local refining. Due to the tendency of PSO to stuck at local minima, PSO obtained less appropriate initial guess as compared to GA in this hybrid method.

In this work, electromagnetic field optimization (EFO) has been utilized to solve the non-linear transcendental equations of selective harmonic elimination. The contributions of the paper are:

1. Development of EFO model for solving SHE problem of a seven level CHB inverter.
2. Switching angles determination for 5th harmonic elimination in a seven level CHB inverter.
3. Development of a simulation model and a hardware platform to test the validity and effectiveness of the EFO algorithm is obtaining the switching angles.

While the sections have been divided as follows. The second section introduces a generalized cascaded MLI structure. By contrasting topological advances with existing MLI structures, Section 3 demonstrates its applicability. In Section 4, it is confirmed that the EFO is superior than well-known SHE-PWM control schemes because it achieves quicker convergence and better harmonic suppression over the wide modulation range. Simulation and experimental verifications are included in Sections 5 and 6, respectively, to confirm the viability of the designed symmetrical MLI in combination with EFO control. The paper is finally concluded mentioning the important points of the work.

2. Electromagnetic Field Optimization (EFO)

EFO is based on the phenomena of physics known as electromagnetism. An electromagnet is a kind of magnet where a magnetic field is created by an electrical current. An electromagnet, as opposed to a permanent magnet, has a single polarity (positive or negative), which is defined by the direction of the electrical current and is modifiable. Additionally, electromagnets are affected by the opposing forces of attraction and repulsion. Electromagnets of opposing polarity attract one another whereas those of the same polarity repel one another. Electromagnets have an attraction force that is (5–10%) greater than a repulsion force. Using these ideas, the method substitutes the golden ratio for the ratio of attraction to repulsion forces. As a result, particles may more fully explore the issue search space and identify a nearly ideal solution. Each solution vector for the population-based EFO method is represented by a single set of electromagnets (electromagnetic particle). The number of variables in the optimization problem determines how many electromagnets make up an electromagnetic particle. As a result, one variable in the optimization problem corresponds to each electromagnetic particle’s electromagnet. Additionally, the polarity of every electromagnetic particle’s electromagnet is the same. However, each electromagnet has the ability to exert an attraction or repulsion force on its peer electromagnets depending on whatever variable in the optimization problem it corresponds to. In EFO, the solution set of the function to be optimized are known as electromagnetic particles. Each electromagnetic contains a certain number of electromagnets that are equal to the number of variables of the problem.

2.1. Search Space Exploration

The EFO explores the search space in the following manner: initially a random population is defined in between which the solution of the function exists. Then the function fitness is evaluated corresponding to the population defined. The function fitness is then sorted according to the best and the worst fitness. Particles are then sorted into three groups: Positive group—consists of certain particles with best fitness and positive polarity; negative group—consists of certain particles with the worst fitness and negative polarity; neutral group—consists of certain particles with the polarity near to the negative but almost neutral. Finally, in each iteration the fitness value of a selected particle is updated. The new updated particle is compared with the worst fitness of the whole population. If the newly generated particle has a better fitness it is kept in the population and the worst particle is eliminated. The updated particle is then kept in the group depending upon its fitness.

2.2. Working of the Algorithm

After the generation of a new particle, it gets the polarity of the neutral particle. Hence, it is attracted toward the positive particle and repelled from the negative particle. This procedure is analogous to getting nearer to the best solution and moving away from the bad solution. Moreover, in order to maintain diversity and avoid local optima the algorithm is designed to show stochastic behavior. Hence, for some of the electromagnetic particles, only one of the electromagnets is replaced by a randomly generated electromagnet. The
mathematical formulation is used in the algorithm which is applied to generate a new position for the randomly selected electromagnet. The position is updated using the formula:

\[
N_{PP_{new}}^k = N_{PP_{new}}^k + \left( (\emptyset \times \text{rnd}) \left( N_{PP_{new}}^P - N_{PP_{new}}^N \right) \right) - \left( \text{rnd} \left( N_{PP_{new}}^N - N_{PP_{new}}^N \right) \right)
\]  

(1)

where \( \text{rnd} \) is the random number generated between 0 and 1, \( N_{PP} \) is the new particle position, \( N_r \) is the random indexing of the neutral group of particles, \( P \) is the indexing of the random particle from the positive group, and \( N \) is the indexing of the particle from the negative group. The Equation (1) is calculated to assign a new position to each electromagnetic of the selected electromagnetic particle. In our case the electromagnetic and the electromagnetic particle are the same terminologies and hence the value of \( k \) will be 1. The flowchart of EFO algorithm is shown in Figure 1.

![Flowchart for EFO algorithm.](image)

Figure 1. Flowchart for EFO algorithm.

The most significant feature of EFO is the high degree of particle cooperation, which accelerates convergence toward global minima. Randomization, which adds variation to the population and prevents the discovery of local minima, is another crucial component of EFO. Additionally, EFO uses the golden ratio to efficiently explore the space for optimization problems. Due to these features, EFO is a reliable optimization technique. The presence of the random variables in every solution will make it impossible to find a satisfactory solution, which is why certain electromagnetic particles have been given a random nature.
But adding randomization to certain solutions makes the population more diverse and avoids local minima.

3. Electromagnetic Field Optimization in Selective Harmonic Elimination

Consider a Cascaded H-Bridge Inverter configuration shown in Figure 2. To generate 5 level output voltage, two cascaded units are required. So, there are two batteries $V_{DC1}$ and $V_{DC2}$, the voltages of which are assumed to be equal. The generation of output voltage waveform is shown in Figure 3.

![Figure 2. Generalized cascaded H-bridge inverter.](image)

The range for switching angles is $0$ to $\pi/2$. Harmonics of even order become zero due to the odd quarter-wave symmetric property. Lower order harmonics are to be eliminated using SHEPWM, and the remaining harmonics are to be filtered out. Without sacrificing generality, a 5-level inverter is used as a case study in this article to get rid of its low-order harmonic (fifth). The amplitude of 5th harmonic with different combination of switching angle is shown in Figure 4. The triplen harmonics need not be considered since they will not exist in three-phase applications. Therefore, two nonlinear equations with two angles are given in order to fulfil the fundamental harmonic and exclude the fifth harmonics. Equations (2) and (3) represent the fundamental and fifth harmonic amplitude present in seven level inverter.
\[
MI = \frac{1}{5} (\cos(\alpha_1) + \cos(\alpha_2)) \tag{2}
\]
\[
V_5 = \cos(5\alpha_1) + \cos(5\alpha_2) = 0 \tag{3}
\]

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure3.png}
\caption{Generation of 5 level output voltage waveform.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{5th Harmonic amplitude for various combination of switching angle.}
\end{figure}

In Equation (3), the fifth harmonics can be eliminated by making \( V_5 \) to zero. A new index called the modulation index is defined to be a representation of \( V_1 \) for achieving different output voltage. Thus, the above two constraints can be combined to form the objective function given by the Equation (4). The objective function also has the THD term.

\[
f(\alpha) = \min_{\alpha_i} \left[ 100 \left| \frac{V_5 - V_1}{V_1} \right| \right]^4 + \sum_{m=2}^{s} \frac{1}{m} \left| 50 \frac{V_{hm}}{V_1} \right|^2 \]
\[
\ldots \text{where, } i = 1, 2, \ldots, s
\]
The electromagnetic field optimization can now be applied to calculate the firing angles. About 1000 iterations are assumed for each run as a termination condition. Where $V_1$ is the required fundamental harmonic, $s$ is the number of switching angles (two in this case), and $h_s$ is the order of the $s$th variable harmonic at the output of the multilevel inverter.

This section identifies switching angles that allow for the elimination of fifth harmonic while increasing the amplitude of the fundamental harmonic to its desired value, or $V_1$.

The first term of (3) defines the fundamental harmonic by a power of 4 if it deviates from its fixed point by more than 1%, the accompanying penalty for any deviations under 1 percent get a minimal value due to the utilization of the power of 4. Harmonics that are less than 2% of the fundamental are ignored in term 2 of Equation (3). However, if any harmonic goes beyond this threshold, the objective function is penalized by a power of two. Each harmonic ratio is then weighted by the harmonic order’s inverse, or $1/h_s$. Reducing the low-order harmonics is given more weight by this weighting mechanism.

The minimal fitness function-based best solution is chosen after the algorithm has been performed 1, 2, 5, and 10 times. The software can effectively reach the answers for viable points. There may be more than one solution for various modulation indices. One of these is encountered by the software. Ten runs have a higher chance of convergent to the global minimum than one. The switching angle variation for different modulation indices and THD vs modulation index variation for EFO has been shown in Figures 5 and 6. In Figure 5, the angles have been expressed in radians. The concentric circle represent the region of same switching angles. That is, points on circle with radius 2 represent switching angle of 2 radians. From Figure 6, it could be observed that the value of THD reduces to less than 20% for values of modulation indices above 0.68 and it is less than 15% for modulation indices lying between 0.75 and 0.95. THD reduces to a minimum value of 9.69% for a modulation index of 0.84.

The MATLAB code for the evaluation of the objective (fitness) function is shown in Table 1.

![Figure 5. Switching angles for 5th harmonic elimination.](image-url)
The THD obtained from EFO algorithm is compared with THD obtained by applying Genetic Algorithm (GA) and Differential Evolution (DE) algorithm. The results are shown in Figure 7. While the THD for lower values of modulation index (0.45–0.6) is significantly lower for EFO algorithm which could be observed from the Figure 7, it is apparently the same for higher modulation index (0.6–1.0). To precisely observe the results better for higher modulation index (0.6–1.0), the improvement factor is shown in Figure 8. The percentage improvement factor is defined as

\[ PIF = THD_{EFO} - THD_{ALG} \]

where ALG is GA and DE

Negative value of THD indicates that the performance of the EFO is better than the other algorithm (GA, DE). The higher amplitude of PIF indicate superior result. Thus, it could be observed that EFO algorithm gives lower THD for quite a good range of higher modulation index.
\[ PIF = THD_{DE} - THD_{GA} \]

where ALG is GA and DE.

Negative value of THD indicates that the performance of the EFO is better than the other algorithm (GA, DE). The higher amplitude of PIF indicate superior result. Thus, it could be observed that EFO algorithm gives lower THD for quite a good range of higher modulation index.

Figure 7. Comparison of THD for DE, GA, and EFO algorithm.

Figure 8. Performance Improvement factor at higher value of modulation index.

4. Simulation Results

The simulation model of the cascaded H-Bridge inverter was developed in MATLAB/SIMULINK environment. The parameters for simulation are tabulated in Table 2.

Table 2. Parameters of simulation model.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Load Resistance (R)</td>
<td>100 Ω</td>
</tr>
<tr>
<td>2.</td>
<td>Load Inductance (L)</td>
<td>100 mH</td>
</tr>
<tr>
<td>3.</td>
<td>Fundamental frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>4.</td>
<td>DC power Supply</td>
<td>( V_{dc1} = V_{dc2} = 100 \text{ Volts} )</td>
</tr>
<tr>
<td>5.</td>
<td>Maximum step size</td>
<td>( 10^{-4} )</td>
</tr>
<tr>
<td>6.</td>
<td>IGBT</td>
<td>Internal resistance Ron = ( 10^{-3} ) Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Snubber resistance Rs = 10.5 Ω</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Snubber capacitance Cs = inf</td>
</tr>
</tbody>
</table>

The output voltage and current waveforms for the five level CHB has been shown in Figure 9 with R load. The harmonic profile of the voltage waveform is shown in Figure 10. It could be seen that the undesirable 5th harmonic which was intended to be removed has negligible contribution in the total harmonic distortion.
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<td>1.</td>
<td>Load Resistance ($R$)</td>
<td>100 Ω</td>
</tr>
<tr>
<td>2.</td>
<td>Load Inductance ($L$)</td>
<td>100 mH</td>
</tr>
<tr>
<td>3.</td>
<td>Fundamental frequency</td>
<td>50 Hz</td>
</tr>
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<td>4.</td>
<td>DC power Supply $V_{dc}$</td>
<td>100 Volts</td>
</tr>
<tr>
<td>5.</td>
<td>Maximum step size</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>6.</td>
<td>IGBT Internal resistance $R_{on}$</td>
<td>$10^{-3}$ Ω</td>
</tr>
<tr>
<td></td>
<td>Snubber resistance $R_s$</td>
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<td>Snubber capacitance $C_s$</td>
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The output voltage and current waveforms for the five level CHB has been shown in Figure 9 with R load. The harmonic profile of the voltage waveform is shown in Figure 10. It could be seen that the undesirable 5th harmonic which was intended to be removed has negligible contribution in the total harmonic distortion.

Figure 9. Simulated 5 level voltage and current waveform.

Figure 10. Harmonic profile of the output five level voltage.

5. Power Loss Analysis

The total power loss in a power electronic converter switches comprises of conduction and switching losses for the proposed inverter is calculated as:

5.1. Switching Loss

The voltage across a typical power switch and current passing through it is approximated to be linear. Equations (7) and (10) gives the energy dissipated during ON and OFF for the $k$th switch.

$$E_{On} = \int_{0}^{t_{on}} v(t)i(t)dt$$  \hspace{1cm} (5)

$$= \int_{0}^{t_{on}} \left( \frac{V_{Sw,k}}{t_{on}} \right) \left( -i_k' \left( t - t_{on} \right) \right) dt$$  \hspace{1cm} (6)

$$= \frac{1}{6} V_{Sw,k} I_k t_{on}$$  \hspace{1cm} (7)

$$E_{Off} = \int_{0}^{t_{off}} v(t)i(t)dt$$  \hspace{1cm} (8)
During a full cycle of the output waveform, by considering the number of turning ON and turning OFF of the switch, the average value of switching losses for each level of output voltage and for each switch is calculated by using Equation (11). Switching pulse of all involved switches is important in order to calculate the switching losses.

\[
P_{sw,j} = \frac{1}{6T} \left[ t_{on} \left( \sum_{k=1}^{N_{on}} V_{sw,k} |I'_j| \right) + t_{off} \left( \sum_{k=1}^{N_{off}} V_{sw,k} |I_j| \right) \right]
\]

The current passing for the \(k\)th power switch and for a \(\lambda\)th level of voltage level when resistive load is taken can be expressed as:

\[
|I_k| = |I'_k| = \left( \frac{\lambda V_{dc}}{R_L} \right) \lambda = 1, 2, 3, 4
\]

Substituting Equation (11) in Equation (12), the value of \(\left( \sum_{k=1}^{N_{on}} V_{sw,k} |I'_j| \right)\) and \(\left( \sum_{k=1}^{N_{off}} V_{sw,k} |I_j| \right)\) the output voltage level can be obtained for each power switch during the generation. The value obtained is shown in Table 2.

Hence, total switching losses of power switch \((P_{sw,t})\) of the proposed inverter is

\[
P_{sw,t} = \frac{1}{6T} \left[ t_{on} \left( \sum_{k=1}^{N_{on}} V_{sw,k} |I'_j| \right) + t_{off} \left( \sum_{k=1}^{N_{off}} V_{sw,k} |I_j| \right) \right]
\]

It is seen from Equation (13) that \(P_{sw,j}\) is proportional to switching frequency and load resistance.

5.2. Conduction Loss

The internal resistance of each component is considered in order to calculate the conduction losses.

The total conduction loss in IGBTs is obtained using:

\[
P_{csw} = V_{swi}(t) + R_s i^b(t)
\]

\[
P_c = \sum_{k=1}^{N_{sw}} \frac{1}{2\pi} \int_0^{2\pi} \left( V_{swi}(t) + R_s i^b(t) \right) dt
\]

\(V_{sw}\) represents the ON state voltage drops across the semiconductor switch. \(R_s\) stands for the ON-state resistance of the switch. The efficiency plot for three methods have been shown in Figure 11. Although DE performs better for power rating below 1200 Watts, the EFO performs better at higher power rating i.e., greater than 1200 Watts) than rest of the algorithm.
EFO performs better at higher power rating i.e., greater than 1200 Watts) than rest of the algorithm.

Figure 11. The efficiency comparison between DE, GA and EFO at a modulation index of \( m = 0.9 \).

6. Hardware Implementation

The simulation results obtained using EFO optimization algorithm for single-phase 5-level CHB-MLI topology are validated using a hardware prototype of the inverter built in the laboratory environment. The experimental set-up along with its components and a simplified block diagram is shown in Figure 12. The experimental system parameters are listed in Table 3.

![Hardware Implementation](image)

Figure 12. Block diagram of the hardware implementation of the EFO algorithm on CHB MLI.

Table 3. Parameters of hardware setup.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameter Description</th>
<th>Value</th>
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<td>100 mH</td>
</tr>
<tr>
<td>3.</td>
<td>Fundamental frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>4.</td>
<td>Microcontroller</td>
<td>TMS320F28379</td>
</tr>
<tr>
<td>5.</td>
<td>Optocoupler</td>
<td>TLP250</td>
</tr>
<tr>
<td>6.</td>
<td>IGBT</td>
<td>IGB20N60H3 (600 V, 20 A)</td>
</tr>
</tbody>
</table>

The output voltage waveform is shown in Figure 13. The load taken is resistive in nature, as focus of the work is to determine the harmonics present in voltage waveform only. The circuit will work fine even with resistive–inductive combination as well. The associated harmonic profile for the 5-level output is shown in Figure 14. The results from GA and DE are also attached in Figures 15–18. While Figures 15 and 16 is for GA, Figures 17 and 18 is for DE. The THD for GA and DE is 29.7% and 30.3% respectively.
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Figure 13. Experimental five level waveform (EFO).

As evident from Figure 13, the peak to peak voltage is 100 V, while the RMS current is 1.24 Amperes. The total harmonic distortion captured on DSO is 29.4%. The THDs are calculated up to 50th harmonics for modulation index of 0.71. According to the harmonic profile, the fifth harmonic is almost absent, and the 3rd, 7th, 9th, and 11th harmonics are computed as 13.4%, 4.5%, 9.2%, and 4.4% of the fundamental harmonic amplitude, respectively.

Figure 14. Harmonic profile (EFO).

Figure 15. Experimental five level waveform (GA).
As evident from Figure 13, the peak to peak voltage is 100 V, while the RMS current is 1.24 Amperes. The total harmonic distortion captured on DSO is 29.4%. The THDs are calculated up to 50th harmonics for modulation index of 0.71. According to the harmonic profile, the fifth harmonic is almost absent, and the 3rd, 7th, 9th, and 11th harmonics are computed as 13.4%, 4.5%, 9.2%, and 4.4% of the fundamental harmonic amplitude, respectively.

7. Conclusions

The paper presented a method of electromagnetic field optimization based selective harmonic elimination in a cascaded H-Bridge five level inverter. The performance of the proposed algorithm was verified in MATLAB-Simulink™ R2016b environment using Intel® Core™ i5, 2.50 GHz workstation. The angles for different modulation indexes were found out in offline mode by solving the objective function using the EFO metaheuristic algorithm and executed as lookup table uploaded in DSC TMS320F28379D. The performance of the algorithm based on total harmonic distortion has been compared with well-established Genetic Algorithm and Deferential Evolution. The EFO algorithm gave
better THD for a large range of modulation indices. The results obtained for the harmonic profile of the output of the five-level inverter was found be satisfactory with 5th order harmonic eliminated almost completely. The hardware results also conform to the results obtained by simulation.

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**Abbreviations**

- $NPP_{N}^{Nw}$: New particle position
- $NPP_{N}^{R}$: random indexing of the neutral group of particles
- $\emptyset$: Golden ratio
- $\text{rnd}$: Random number
- $NPP_{P}^{P}$: P is the indexing of the random particle from the positive group
- $NPP_{N}^{N}$: N is the indexing of the particle from the negative group
- $\alpha_1$: Switching angle 1
- $\alpha_2$: Switching angle 2

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