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Elimination of Lower Order Harmonics in Multilevel Cascaded Inverters with Equal Dc Sources using Pso

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***Abstract* – This paper presents elimination of lower order harmonics in multilevel inverters withequal DC sources using PSO. To eliminate the selected lower order harmonics from the output voltage or current waveform of a cascaded multilevel inverter, appropriate switching angles were calculated and the power switching devices were switched accordingly. The switching angles were calculated from the non-linear equations derived from the Fourier series expansion of the output voltage of the inverter. A PSO algorithm was developed to solve the nonlinear equations. With the proposed approach, the required switching angles are efficiently computed using PSO to eliminate the lower order harmonics from the inverter voltage waveform for different modulation indices (ma).The PSO algorithm was developed in the Matlab environment, and the three phase multilevel cascaded inverter systems have been simulated using the PSIM software. The performance of the proposed method for a nine-level cascaded H-bridge inverter was evaluated based on simulation and experimental studies. Lower order harmonic up to the 11th order are eliminated.**

***Keywords*– Lower Order Harmonic, Multilevel Inverter, Equal DC Sources.**

I. INTRODUCTION

In recent years, research related to multilevel inverters has received considerable attention for either high voltage or high power applications. When the number of levels in a given topology increases, the output voltage will contain more steps, which generates a staircase waveform that closely approaches the desired sine wave waveform. Multilevel inverters reduce the amplitude of inverter-generated harmonics and the stresses across the semiconductor, eliminate the need for series connections of semiconductors, improve the total harmonic distortion (THD) and decrease the dV/dt of the output voltage waveform [1]. Thus, various multilevel inverter configurations have been studied and investigated for different applications over the past few decades [2]-[7].

The three most important multilevel inverter topologies are diode clamps [8], flying capacitors [9] and cascaded multilevel inverter with separate DC sources [10]. Among the above multilevel inverter structures, H-bridge or cascaded multilevel inverters are particularly attractive because of their modularity and simplicity of control. However, various researchers are actively investigating the modulation schemes of inverters to improve the operating performances for different applications [11]-[13]. A variety of pulse width modulation (PWM) schemes commonly used for cascaded multilevel inverters are based on the following methods: 1) sinusoidal PWM (SPWM); 2) space vector PWM (SVPWM); 3) non-Sinusoidal carrier PWM; 4) mixed PWM; 5) special structure of cell connections and 6) selective harmonic elimination PWM (SHEPWM). Because multilevel inverters usually operate with a low switching frequency, SHEPWM offers several advantages over the other methods such as a low switching frequency with a wider converter bandwidth, direct control over lower order harmonics and better DC source utilization [14]-[16]. SHEPWM is also the most famous switching strategy that is widely used to specifically eliminate the selected order harmonics from the output waveform of the inverter. The main objective of the selective harmonic elimination is to eliminate or minimize the lower order harmonics or the harmonics close to the fundamental.

However, solving the nonlinear SHEPWM equations is a major problem in obtaining the switching angles. To date, there are a number of methods have been proposed to solve the nonlinear equations of SHEPWM, such as the Newton-Raphson method [17].

This method requires a good initial guess that should be very close to the solution. Although the Newton-Raphson method works well if a good initial guess is available, providing a good guess is very difficult in most cases. Lately, methods based on a Genetic Algorithm (GA)[18], bacterial foraging [19], Bee algorithm [20] and PSO [21] were introduced to solve the problem related toIn this paper, the PSO algorithm is applied to minimize lower order harmonics, and to satisfy the desired fundamental component for a multilevel cascaded inverter for equal

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DC sources. A nine-level inverter was selected as a case study.

II. MULTILEVEL INVERTER AND SHEPWM

Multilevel inverters convert power in multilevel voltage steps to improve the power quality, lower switching losses, improve the electromagnetic compatibility and increase the voltage capability [22]. Fig. 1 shows a three-phase cascaded multilevel inverter. Cascaded multilevel inverter consists of a series of H-bridge (single-phase full bridge) units. Each H-bridge can generate three different voltage outputs + Vdc 0 and –Vdc. However, all four multilevel inverters for each phase can produce a staircase waveform, as shown in Fig. 2. The number of levels (m) in the output phase voltage is 2s+1, where s is the number of H-bridges used for every phase. The magnitude of the cascaded nine -level inverter is given by the following:

$$V_{AN} = V_{dc1} + V_{dc2} + V_{dc3} + V_{dc4} \quad (1)$$

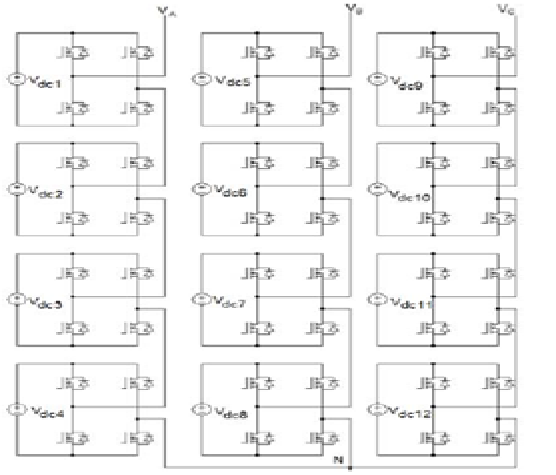

Fig. 1. Three phase cascaded multilevel inverter

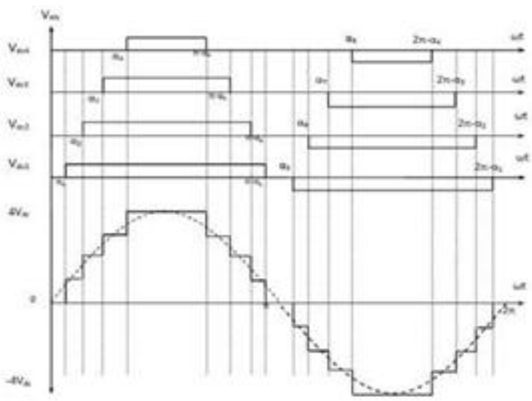

Fig.2. The output voltage waveform of a nine-level inverter.

The nine level waveform shown in Fig. 2 has four variables α1, α2, α3 and α4.The Fourier series expansion of a multilevel inverter is given by Eq. (2):

$$V_{AN}(\omega t) = \sum_{n=1,3,5,...}^{\infty} \frac{4V_{dc}}{n\pi}(V_{dc1}\cos(n\alpha_1) + V_{dc2}\cos(n\alpha_2) + V_{dc3}\cos(n\alpha_3) + V_{dc4}\cos(n\alpha_4))\sin(n\omega t) \quad (2)$$

V_{dc} is the input cell voltage for each H-bridge. For equal DC sources V_{dc1}, V_{dc2}, V_{dc3}, and V_{dc4} are equal. For a nine-level inverter and a given desired fundamental peak voltage, the switching angles need to be determined such that $0 \le \alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 \le \pi/2$ and the predominant lower order harmonics of the phase voltage are zero. For triple harmonics i.e, 3rd, the 9th order should not be taken into account because it will vanish in a three-phase system. The required switching angles to eliminate the 5th, 7th and 11th order harmonics at the fundamental switching frequency for a nine- level cascaded inverter can be calculated by solving the following equation:

$$\begin{aligned} &V_{dc1}\cos(\alpha_1) + V_{dc2}\cos(\alpha_2) + V_{dc3}\cos(\alpha_3) + V_{dc4}\cos(\alpha_4) = sm_a \\ &V_{dc1}\cos(5\alpha_1) + V_{dc2}\cos(5\alpha_2) + V_{dc3}\cos(5\alpha_3) + V_{dc4}\cos(5\alpha_4) = 0 \\ &V_{dc1}\cos(7\alpha_1) + V_{dc2}\cos(7\alpha_2) + V_{dc3}\cos(7\alpha_3) + V_{dc4}\cos(7\alpha_4) = 0 \\ &V_{dc1}\cos(11\alpha_1) + V_{dc2}\cos(11\alpha_2) + V_{dc3}\cos(11\alpha_3) + V_{dc4}\cos(11\alpha_4) = 0 \end{aligned} \quad (3)$$

where s is the number of H-bridges per phase and m_a is a modulation index and defined as:

$$m_a = \pi V_1/(4V_{dc}) \quad (4)$$

To ensure that the lower order harmonics are eliminated, an objective function is required for the optimization process.

Designing a good objective function is very important to ensure the lower order harmonics are completely eliminated. Thus, the objective function for the nine-level inverter that ensures that the 5th, 7th and 11th harmonics are eliminated is:

$$F(\alpha_1,\alpha_2,\alpha_3,\alpha_4) = \left[\sum_{n=1}^{s} V_{dc1}\cos(\alpha_n) - sm_a\right]^2 + \left[\sum_{n=1}^{s} V_{dc2}\cos(5\alpha_n)\right]^2 + \left[\sum_{n=1}^{s} V_{dc3}\cos(7\alpha_n)\right]^2 + \left[\sum_{n=1}^{s} V_{dc4}\cos(11\alpha_n)\right]^2 \quad (5)$$

International Journal of Scientific Research & Engineering Trends
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III. PSO ALGORITHM

Kennedy and Elberhart developed PSO in 1995 based on swarm behavior, such as fish and bird schooling in nature [23]. It is an evolutionary technique similar to the Genetic Algorithm (GA), because both are population-based and equally effective. However, PSO is more efficient, especially in terms of computational efficiency.Thus, PSO requires less memory space and CPU speed, and fewer parameters need to be adjusted. Thus, the PSO method is gaining popularity due to its simplicity of implementation and ability to quickly converge to a reasonably good solution.

In PSO, each particle in a swarm represents a solution to the problem and is defined by its position and velocity Each particle is placed in the search space problem or a specific function. For each particle, the objective function is calculated at the current location. All particles have fitness values that are based on the position and velocity of the particle flight instructing them. The PSO is initiated by a group of random particles (solutions), and it then searches for the optimal by updating generations. For each iteration, each particle is updated by two of the best values, Pbest (best present) and Gbest (global best). The particle velocity and position are subsequently updated using the following equation:

$$V(n+1) = W \cdot V(n) + C_1 \cdot rand\big(Pbest - \alpha(n)\big) + C_2 \cdot rand(Gbest - \alpha(n)) \quad (6)$$

$$X(n+1) = X(n) + V(n+1) \quad (7)$$

Where, C1 and C2 are constriction factors ranging from 1 to 2. Pbest, Gbest and present α are the Pbest, Gbest and present values of a variable α respectively. W is the inertia weight and its value depends on the type of problem and the search criteria. If the selected value is large, it facilitates the global exploration, if the selected value is small; it tends to facilitate local exploration to fine tune the current search area. Therefore, the selection of the appropriate W can provide a balance between global and local exploration abilities. It will subsequently decrease the number of iterations to find the optima.
Moreover, rand stands for random values in the range [0, 1]. The step by step algorithm for proposed optimal switching angles is given below:

1. Randomize angles through for initial guess Corresponding to the number of population (n) based on $0 \le <<< \le \pi/2$
2. Evaluate fitness function, F(α)
3. Updating personal best position, Pbest
4. Updating global best position, Gbest
5. Evaluating velocity and compute new value of
6. Checking stopping criteria
7. Obtaining final fitness function, F(α)
8. End PSO process

The PSO algorithm was implemented in the Matlab environment. Table I summarizes the parameters used in the PSO algorithm to solve the nonlinear equation.
The algorithm is run for 1 and 20 times and the best solution based on the minimum objective function value is selected.

TABLE I
PARAMETRES OF PSO ALGORITHM

PSO parameter	Value
Swarm size	100
Maximum iterations	200
Inertia weight factor	0.9
C_1	2
C_2	2

The proposed scheme is applied to a nine- level inverter to eliminate the 5th, 7th and 11th harmonics with equal DC sources. Fig. 3 shows the optimum value of the objective function versus the modulation index. The modulation index increases by 0.01 for each step. The benchmark value of the objective function used to asses whether the harmonics has been successfully eliminated is 10-2 [19]. Thus, Eq. (3) has a feasible solution or the PSO program has reached global minima when the fitness function is less than 10-2. Based on the graphs in Fig. 3 the feasible regions in which the harmonics are eliminated are limited to 0.31≤ma≤0.35, 0.41≤ma ≤0.88 and 0.9≤ma≤0.94. In these regions, the quantity of the lower order harmonics almost reaches Zero. For other values of the objective function, solutions might not be achieved at all, where the algorithm has converged in local minima or stop at stopping criteria.
From Fig. 3 the optimum objective function occurs at maequal 0.7. The switching angles solutions against madepicted in Fig. 4.

IV. SIMULATION RESULTS

The simulation was performed using the PSIM software to validate the computational results of switching angles. The nominal DC voltage is considered to be 48V (1p.u) and equal for all bridges (Vdc1 until Vdc12). The simulation was performed for the entiremodulation index from 0.3 to 1 with a step increase of 0.01.

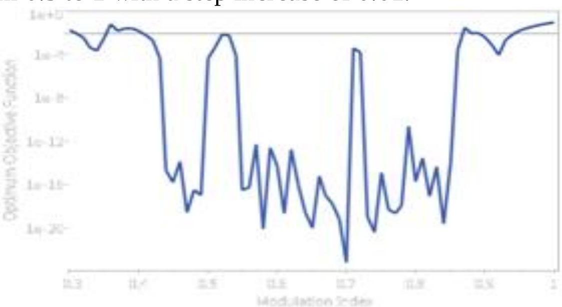

Fig.3. Optimum value of the Objective Function versus modulation index.

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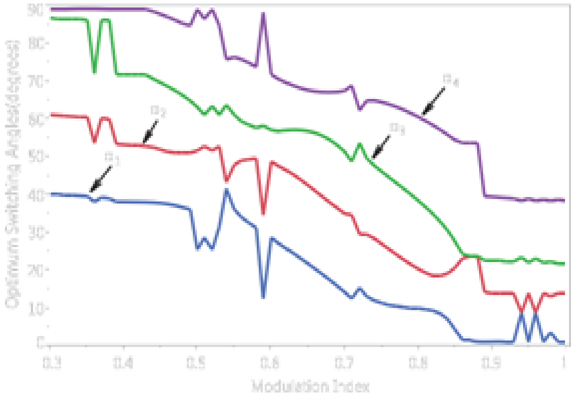


Fig. 5 shows THD against the modulation index for line voltage. The lowest THD occurs at ma equal 0.82. The THD is calculated based on Eq. (8):

$$THD = \frac{\sqrt{\sum_{n=5,7,11..}^{49} V_n^{\,2}}}{V_1} \times 100 \qquad (8)$$

The output phase voltage, line- to- line voltage and harmonic spectra of the line- to -line voltage for ma equal to 0.7 is depicted in Figs. 6. The 5th, 7th and 11th harmonics are eliminated. The first harmonic to appear is the 13th harmonic. Figs. 7 show the output phase voltage, line- to- line voltage and harmonic spectra of the line- to -line voltage for ma equal to 0.82.

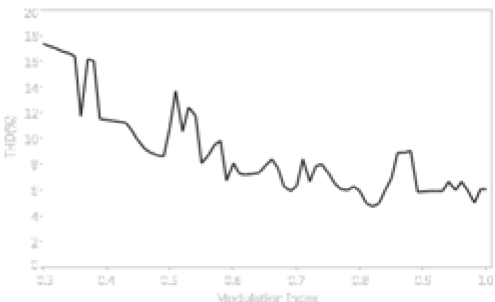
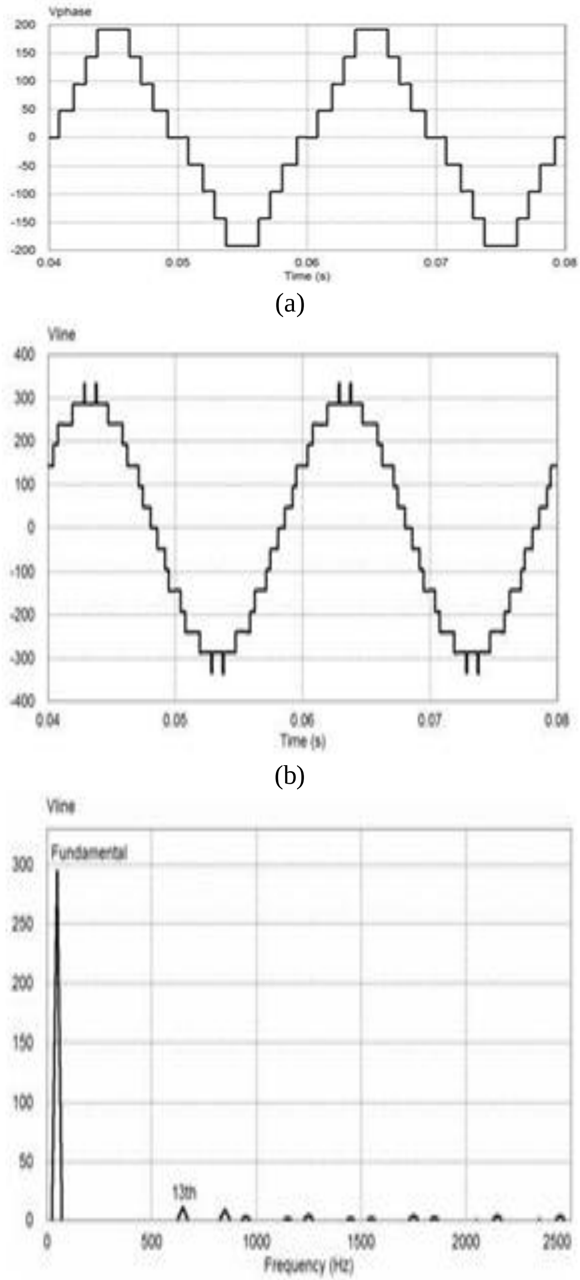


Fig. 5. THD for line voltage versus modulation indexof equal dc sources.

The 5th, 7th and 11th harmonics are eliminated. The first harmonic to appear is the 13th harmonic.

V. EXPERIMENTAL RESULTS

To verify the simulation results, a three phase, nine-level inverter was experimentally investigated. To validate the results obtained from the simulations, a three phase nine-level cascaded inverter prototype was developed in the laboratory. Four switching H-bridges with power MOSFET IRFP250 and a rating of 200V/33A were designed for every phase. The switching angles were implemented on a DE0 Altera field programmable gate array (FPGA) cyclone III board. The crystal frequency of the FPGA was set to 50MHz (equal to 2×10 seconds) to ensure fast and reliable operation. The counter value was the set to 1,000,000 counts for 2×10 seconds, and the appropriate switches were set to ON and OFF for certain intervals depending on the switching angles to be applied.



(a)

(b)

(c)

Figs. 6. Simulation results for m_a= 0.7.(a) Output phase voltage . (b) Output line- to -line voltage. (c) Harmonic spectra of line- to- line voltage

International Journal of Scientific Research & Engineering Trends
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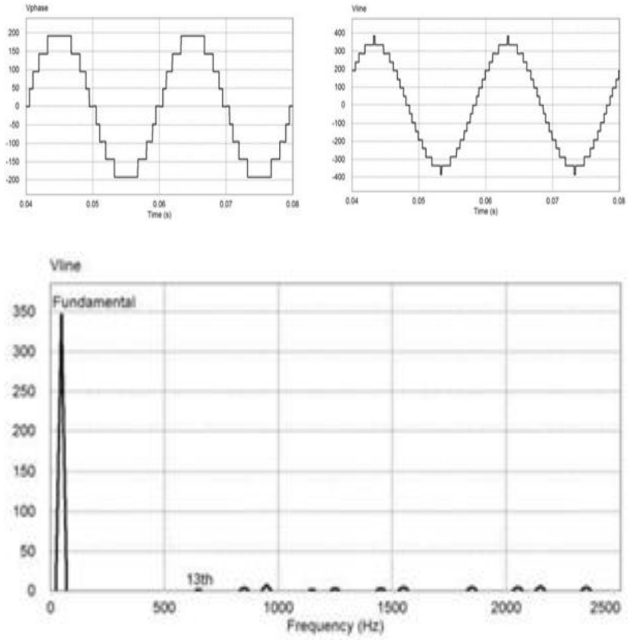
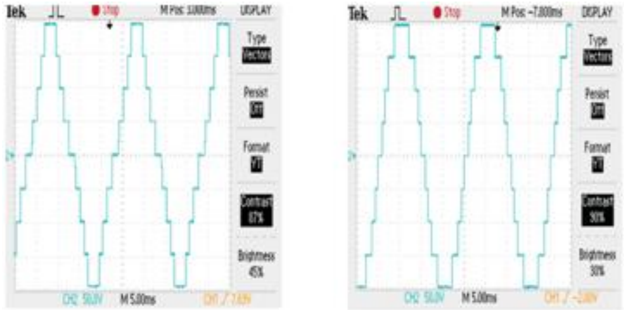


Fig 7. Simulation results for ma= 0.82. (a) Output phase voltage (b) Output line- to -line voltage. (c) Harmonic spectra of line- to- line voltage.

The FPGA board transferred the switching pulses to the gates of the power MOSFET via an optocoupler A3180 isolate the power MOSFET from the FPGA. The switching pulses were then transferred to the power MOSFET driver which was connected to the MOSFET and supplied the required 15V for turning the MOSFET to ON.

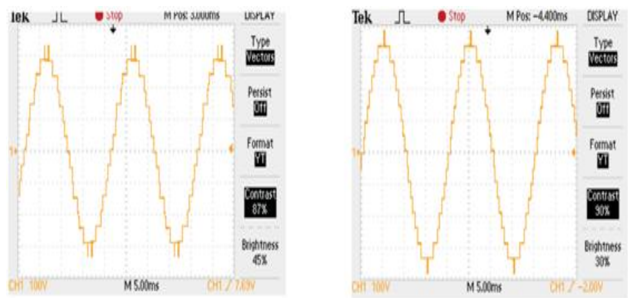
TABLE II
EXPERIMENTAL AND SIMULATION THD SUMMARY

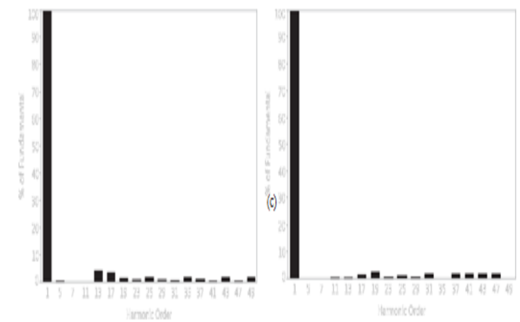
m_a	Switching angles (Degree)				THD (%) Calculated by equation (8)	
	α_1	α_2	α_3	α_4	Experiment	Simulation
0.70	14.31	34.82	51.16	67.48	6.33	6.36
0.82	9.28	18.69	34.87	58.30	4.67	4.73



The DC side of the multilevel inverter was supplied by a constant 48V DC source. Twelve separate 48V DC supplies were used to power the H-bridges. A Tektronik TPS 2014 digital storage oscilloscope was used to record the output voltage waveform and Total Harmonic Distortion (THD). Fig. 8 shows the experimental set-up of three phase cascaded nine-level inverter. Figs. 9 show the experimental output phase voltage waveform, line- to-line output waveform and harmonic spectra of the line-to- line voltage for a ma equal to 0.7. The harmonic spectra of the line- to- line voltage indicates that the lower order harmonics i.e., the 5th, 7th and 11th harmonic are eliminated.

The THD value is 6.33%. Figs. 10 show the experimental output phase voltage waveform, line- to-line output waveform and harmonic spectra of the line-to- line voltage for a ma equal to 0.82 with equal dc sources. The harmonic spectra of the line- to- line voltage indicates that the lower order harmonics i.e., the 5th, 7th and 11th harmonic are eliminated. The THD value is 4.67%.





Figs. 9. Experimental results for m_a= 0.7(a) Output phase voltage (b) Output line- to- line voltage (c) Harmonic spectra of line- to- line voltage

Figs. 10. Experimental results for m_a= 0.82 (a) Output phase voltage. (b) Output line- to- line voltage (c) Harmonic spectra of line- to- line voltage

VI. CONCLUSION

In this paper, the elimination of lower order harmonics for a cascaded multilevel inverter with equal DC sources was investigated. The PSO technique could effectively find the optimal solutions although in a notably short time based on different values of the modulation index. However, at some modulation index, the lower order harmonics cannot be removed and thus should be minimized. The provided simulation and experimental results agree for all cases examined in this study.

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