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Harmonic Elimination of Hybrid Multilevel Inverters Using Particle Swarm Optimization

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***Abstract*—**This paper present the harmonic elimination of hybrid multilevel inverters (HMI) which could be increase the number of output voltage level. Total Harmonic Distortion (THD) is one of the most important requirements concerning performance indices. Because of many numbers output levels of HMI, it had numerous unknown variables of eliminate undesired individual harmonic and THD nonlinear equations set. Optimized harmonic stepped waveform (OHSW) is solving switching angles conventional method, but most complicated for solving as added level. The artificial intelligent techniques are deliberation to solve this problem. This paper presents the Particle Swarm Optimization (PSO) technique for solving switching angles to get minimum THD and eliminate undesired individual harmonics of 15-levels hybrid multilevel inverters. Consequently it had many variables and could eliminate numerous harmonics. Both advantages including high level of inverter and Particle Swarm Optimization (PSO) are used as powerful tools for harmonics elimination.

***Keywords*—**Multilevel Inverters, Particle Swarms Optimization, Harmonic Elimination.

I. Introduction

RECENTLY, multilevel converters are widely used in industry, power system applications such as flexible AC transmission systems (FACTS) devices [1], high voltage direct current transmissions (HVDC) [2] and distributed generation (DG) systems [3]. The direct connection of a single semiconductor switch to a system with medium sized voltage grid (2.3-6.9 kV) is too complex [4]. To overcome the limitations on semiconductor voltage and current ratings, some type of series connection will be necessary. Due to their ability to synthesize waveforms with a better harmonic spectrum and attain a higher voltage without transformers, they have drawn attention in the past few years.

The well-known multilevel topologies are cascade H-Bridge, neutral-point clamp or diode-clamped and flying capacitor [5], [6], [7]. Diode-clamped and flying capacitor multilevel inverters is not only simple and modular but also requires least number of components and clamping diodes or voltage balancing capacitors. The multilevel inverter composed of H-Bridges (HBs) with separate dc source. The results phase voltage is synthesized by the addition of voltages generated by the different HBs. If the DC-link voltages of HBs are identical, the multilevel inverter is called the cascade multilevel inverter (CMI). However, it is possible to have different values among the HBs DC-link voltages and the circuit calling as the hybrid multilevel inverter that generated high number of output voltage level.

Today, there are many switching strategies which applied to multilevel inverter topologies such as pulse width modulation (PWM), sinusoidal pulse width modulation (SPWM), space vector modulation (SVM), selective harmonic eliminated pulse width modulation (SHEPWM), all of various switching methods produce harmonics and hence, it is interested in selecting the best method to achieve minimum harmonic and total harmonic distortion (THD). It is suggested that using optimized harmonic stepped waveform (OHSW) to eliminated low order harmonic by determining proper angles and removing the rest of the harmonic via filters.

This paper focuses on total harmonic elimination method with hybrid multilevel inverters by using the particle swarm optimization (PSO) algorithm.

II. Hybrid Multilevel Inverter Structure

The basic structure of hybrid multilevel inverter is base on connection of H-Bridges (HBs). Fig. 1 shows the circuit for one phase leg of a multilevel inverter with three HBs in each phase. Each HB is supplied by a separate DC source. The resulting phase voltage is synthesized by addition of the voltages generated by difference HBs. If the DC-link voltages of HBs are identical, is called CMI. However, it is possible to have different values among the DC-link voltages of HBs, and the circuit could be called hybrid multilevel inverter (HMI).

A. Cascade Multilevel Inverters (CMI)

In a cascade multilevel inverter (CMI), the DC-link voltages of HBs are identical. In three-HB one phase leg Dc-link voltages are $V_{DC1}=V_{DC2}=V_{DC3}=E$, where E is the unit voltage. The number of output level are normalized by

$$L = 2N + 1 \tag{1}$$

where L is the number of output level
N is the number of HBs

Each HB generates at the output: $+E$, 0 and $-E$. This is possible by connecting the capacitors sequentially to the AC side via three power switches. The resulting output AC voltage swing from $-3E$ to $3E$ with seven levels.

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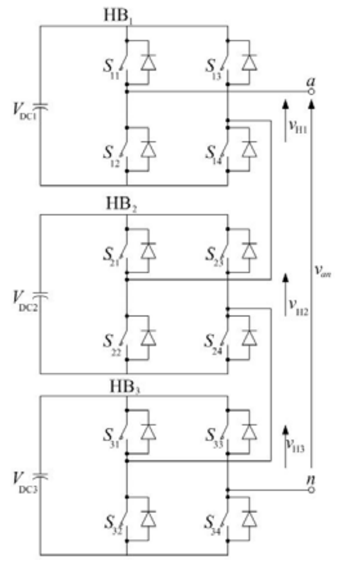

Fig. 1 Multilevel inverter based on the connection of HBs

B. Binary Hybrid Multilevel Inverter (BHMI)

In binary hybrid multilevel inverter (BHMI), the DC-link voltage of HB_i (the ith HB), $V_{\mathrm{DC}i}$ are $2^{i-1}E$. In three-HB one phase leg $V_{\mathrm{DC1}}= E$, $V_{\mathrm{DC2}}= 2E$ and $V_{\mathrm{DC3}}= 4E$. The number of output level are normalized by

$$L = 2^{N+1} - 1 \tag{2}$$

As shown in Fig. 2, the output waveform. v_{an}, has 15 levels. One of the advantages is that HB with higher DC-link voltage has a lower number of commutations, thereby reducing the associated switching losses. The BMHI illustrates a seven-level (in half-cycle) inverter using this hybrid topology. The HB with higher DC-link voltage consists of a lower switching frequency component, for example, IGBT, are used to construct the HB with lower DC-link voltages.

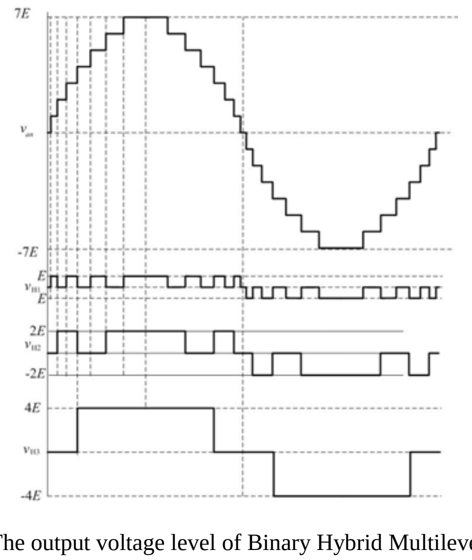

Fig. 2 The output voltage level of Binary Hybrid Multilevel Inverter

The number of output level of two, three and four-HBs are shown in Table I, its compare different type of multilevel inverters base on the connection of HBs.

TABLE I
NUMBER OF OUTPUT VOLTAGE LEVELS

No. of HBs	Type of MI	$V_{\mathrm{DC}i}$	No. of level
2	CMI	E	5
	BHMI	$2^{i-1}E$	7
3	CMI	E	7
	BHMI	$2^{i-1}E$	15
4	CMI	E	9
	BHMI	$2^{i-1}E$	31

C. Switching Function

The positive switching functions of 15-levels BHMI inverter are shown in Table II. As a negative case, it is easily obtained by multiplying -1.

TABLE II
SWITCHING FUNCTION OF 15-LEVEL BINARY HYBRID MULTILEVEL INVERTER

Level	Switch function			Terminal voltage			Output Voltage
	HB1	HB2	HB3	v_{H1}	v_{H2}	v_{H3}	
0	0	0	0	0	0	0	0
1	1	0	0	1	0	0	1E
2	0	1	0	0	2	0	2E
3	1	1	0	1	2	0	3E
4	0	0	1	0	0	4	4E
5	1	0	1	1	0	4	5E
6	0	1	1	0	2	4	6E
7	1	1	1	1	2	4	7E

III. HARMONICS ELIMINATION STRATEGIES

One of the main concerns and performance indicators of inverter is level of total harmonic distortion (THD) in its output waveform. Harmonics could significantly reduce the efficiency of an inverter as well as damage other devices that connected to it. For this reason IEEE has published the IEEE standards 519-1992, describing harmonic requirement all inverters should meet.

The harmonic elimination topic has been extensively studied and researchers have developed countless diverse techniques. Selecting one of these techniques depends greatly on the topology of inverter as well as its intended application. For multilevel inverter topologies, there are four well known techniques that demonstrate their advantages and disadvantage, these techniques are sinusoidal pulse width modulation (SPWM), space vector modulation (SVM), selective harmonic elimination (SHE) and optimized harmonic stepped waveform (OHSW) [8-11].

In this paper, OHSW technique is the primary consideration as theoretically provide the lowest THD for high level multistep inverters without using filter.

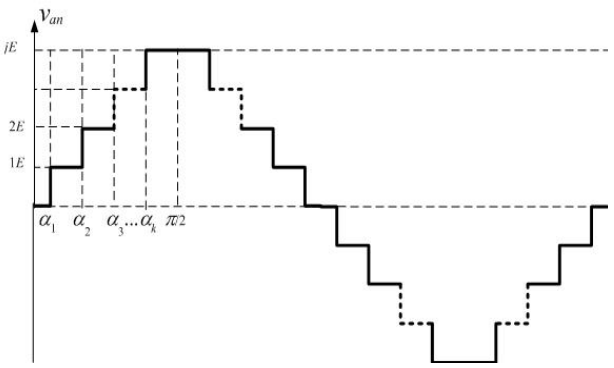

Fig. 3 Quarter-symmetry stepped-voltage waveform

A. Selective Harmonic Elimination (SHE)

The selective harmonic elimination (SHE) is a technique in which the switching angles of an inverter are calculated offline so could terminate out different order harmonic. SHE, detailed explanation calculate the angles for SHE is given by Patel [10]. Mathematically, the waveforms are calculated by solving a set of nonlinear equations governing amplitude of each individual harmonic. SHE technique is the most difficult in the four to solve, and greatly increases as added levels.

B. Optimized Harmonic Stepped Waveform (OHSW)

The optimized harmonic stepped waveform (OHSW) is very similar to SHE except that it is better suited for higher level multilevel inverters and could reduce the THD without filters. Similar to SHE, the switching angles are calculated offline consequence minimizing any undesired harmonics.

Considering Fig. 3, with equal amplitude of all stepped voltage level, the Fourier series expansion of this waveform is

$$v(\omega t) = \sum_{n=1}^{\infty} H_n(\alpha)\sin(n\omega t) \tag{3}$$

where, H_n is the amplitude of the harmonics. The angles are limited to between zero and 90^o ($0 \le \alpha \le 90^o$). Because of an odd quarter-wave symmetric characteristic, the harmonics with an even order become zero. Subsequently, H_n becomes

$$H_n(\alpha) = \frac{4E}{n\pi}\sum_{k=1}^{L-1}\cos(n\alpha_k) \quad \text{, for all odd } n \tag{4}$$

$$H_n(\alpha) = 0, \quad \text{,for all even } n \tag{5}$$

where L is the number of levels
n is an odd harmonic orders
α_k is the kth switching angles
E is the amplitude of voltage levels

In this paper, the three-HBs is chosen as a study. In general solving a set of switching angles for an L- level inverter requires solving (L-1)/2 equations each with nonlinear terms. For 5-level inverters, it is possible with reasonably educated starting guesses to use conventional techniques such as Newton to solve for the angles. As the level increase these techniques become less effective due to the large number of local minima. Newton method had a difficult to solve for a set of firing angles.

IV. Particle Swarm Optimization

The particle swarm optimization (PSO) is an optimization technique first introduced by Kennedy and Eberhart [12] to model the social interaction of a flock of birds or school of fish.

The basic concept of PSO is to assume that an optimal solution could be reached by a swarm of n particles that could exchange information. In PSO, each particle has a position and velocity and the position of each particle represents a potential solution to the optimization problem. During each iteration the position of each particle is evaluated by and objective function and at the end updates are made to each particle velocity and position. A particle's velocity is updated by a contribution of three things: the particle's current velocity, the particle's best position, and the best position found by any particle. Once the particle's velocity is updated, it is used to update the particle's position. This process is repeated until either a tolerance or maximum number of iteration is reached. The final solution is taken to be the best position found by any particle [14], [15], [16], [17], [18], [19].

If x_i is the current position of the particle in the swarm, its new position will be

$$x_i^{k+1} = x_i^k + v_i^{(k+1)}.\Delta t \tag{6}$$

where v^{k+1} is the new velocity of each particle i of the swarm. It is update by

$$v_i^{(k+1)} = w.v_i^k + p.\alpha_i(x_i^{pbest} - x_i^{(k)}) + g.\beta_i(x_i^{gbest} - x_i^{(k)}) \tag{7}$$

where α_i, β_i is an uniformly distributed random in [0, 1]. w is a weight coefficient introduce to give some inertia to the movement, so that the bird couldnot change directional abruptly. p and g are increment amounts by which the speed could be changed according to the personal best position and the general best position of the swarm x_i^{pbest} is the personal best position particle i and x_i^{gbest} is the general best position of the swarm.

A. Defining the Optimization Problem

The optimization problem as defined by Barkati [13] is to solve, for given modulation index, a series of equations defined by (3).

Fig. 4 are shown the step wave form to firing switching angles, for three-phase inverter using quarter wave symmetry, containing L-levels, k switching angles, and j number of half cycle levels, the system of equations to be solved contain k nonlinear equations and is represented by the following

$$\begin{aligned} \cos(\alpha_1)+\cos(\alpha_2)+...+\cos(\alpha_k) &= \frac{jM\pi}{4} \\ \cos(5\alpha_1)+\cos(5\alpha_2)+...+\cos(5\alpha_k) &= 0 \\ \cos(7\alpha_1)+\cos(7\alpha_2)+...+\cos(7\alpha_k) &= 0 \\ &\vdots \\ \cos(n\alpha_1)+\cos(n\alpha_2)+...+\cos(n\alpha_k) &= 0 \end{aligned} \tag{8}$$

B. Solving Switching Angles with PSO

To solve the switching angle with PSO the first step is to identify constrains and objective function. The constrain demand that all of the switching angles must be in increasing order and maintain quarter-wave symmetry. To keep symmetry every angle must be greater than 0 degree and less than 90 degrees.

$$\text{Constraints: } 0 \le \alpha_1 \le \alpha_2 \le ... \le \alpha_k \le \frac{\pi}{2} \tag{9}$$

The objective is to find the switching angles to force the component odd harmonics to zero while keeping the relative fundamental component at a desired follow

$$H_1^{ref} = \frac{V_{ref}}{E} \tag{10}$$

where V_{ref} is the reference output voltage

The objective function, also called the fitness function or cost function are represent the overall equation that should minimized.

$$\text{Cost Functions; } w_1\left|jM - H_1\right| + w_2\left|H_5\right| + ... + w_k\left|H_n\right| \tag{11}$$

where M is the modulation index defined as (12)

$$M = \frac{V_{ref}}{jE} \tag{12}$$

The w_1 through w_k represent different weights allowing different amounts of importance to be assigned to different harmonics. The first component of equation $w_1\left|jM\text{-}H_1\right|$ guarantees that the p.u. amplitude of the fundamental will be equal to the modulation index. The rest of the components eliminate particular individual harmonics. The flow chart are shown in Fig.5

C. Performance Index

In order to indicate the usefulness and effectiveness of the presented method, a quality factor is chosen as a performance index. The THD is very useful parameter to evaluate the performance of the inverter, and therefore it is considered in this work. The THD is defined as the total amount of harmonics relative to the fundamental, and could be calculated using (13).

$$\%THD = \frac{\sqrt{\sum_{n=5,7,...}^{\infty} H_n^2}}{H_1} \times 100 \tag{13}$$

where H_n is amplitude of harmonic nth orders and H_1 is amplitude of fundamental frequency. In this paper the THD are calculated up to the 101[st] harmonic.

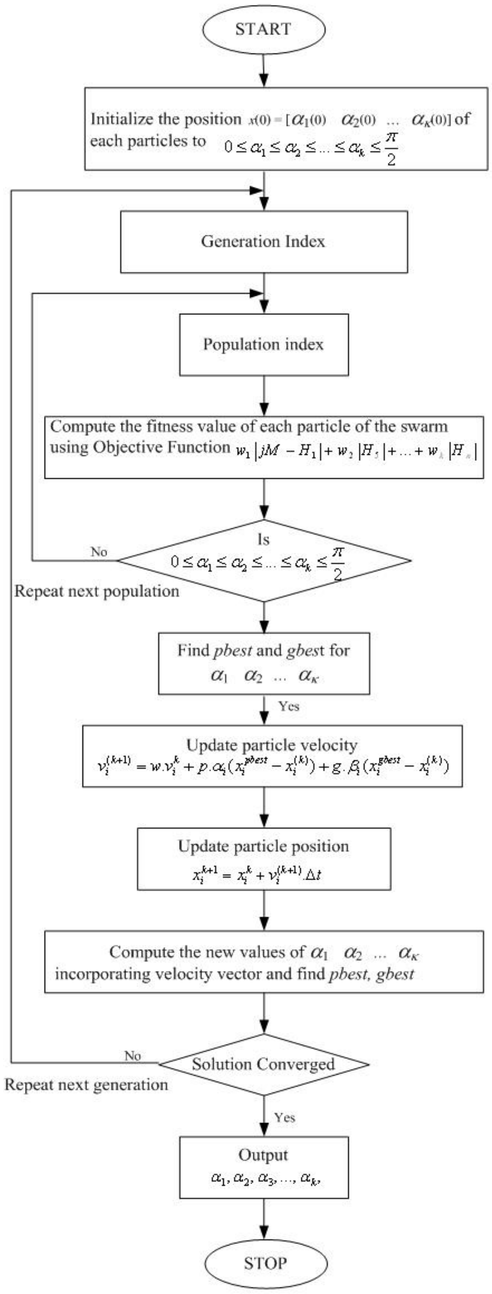

Fig. 4 PSO Flow Chart for calculate switching angle

V. Simulation Results

For three-HBs BHMI inverter is generated 15-level, the seven equations to be solved switching angles, switching angles k=7. For three phase applications, the add harmonics up to 19th orders are eliminated, and seven equations to be solved at 15-level. The objective function or cost function is given by:

$$F(\alpha_1,\alpha_2,\alpha_3,...,\alpha_7) = w_1\left|7M - H_1\right| + w_2\left|H_5\right| + w_3\left|H_7\right| + ... + w_7\left|H_{19}\right| \tag{14}$$

The simulation results is run for 50 particles with w = 1, p = 1.8, g =1.8 and modulation index step=0.0001 from 0.4 to 1.0. The switching angles versus Modulation index, the final cost of each solution, THD, and any individual harmonic amplitudes in M=0.90 are shown in Fig. 5 to Fig. 8 respectively.

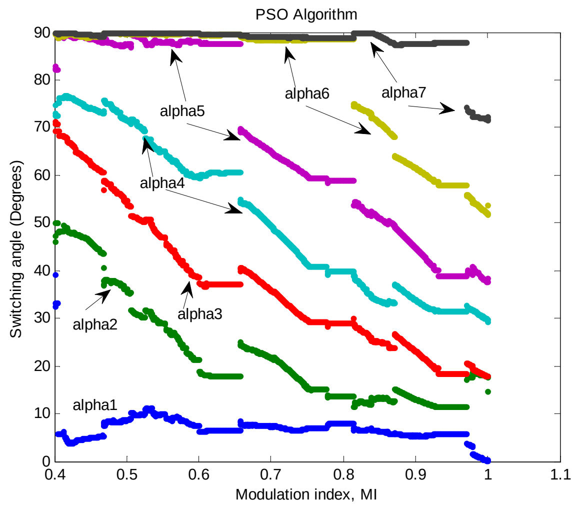

Fig. 5 Switching angles versus the modulation index

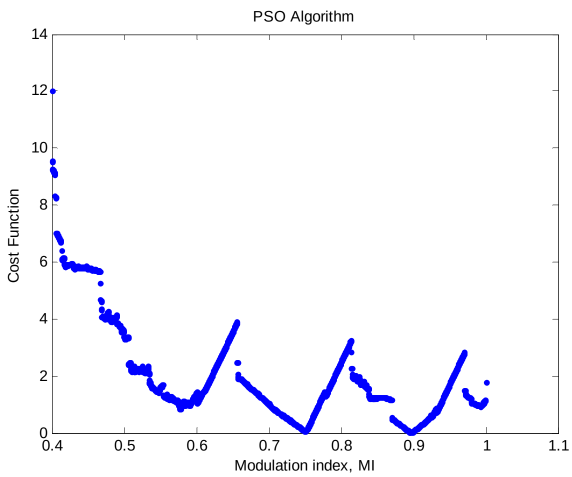

Fig. 6 Cost function versus the modulation index

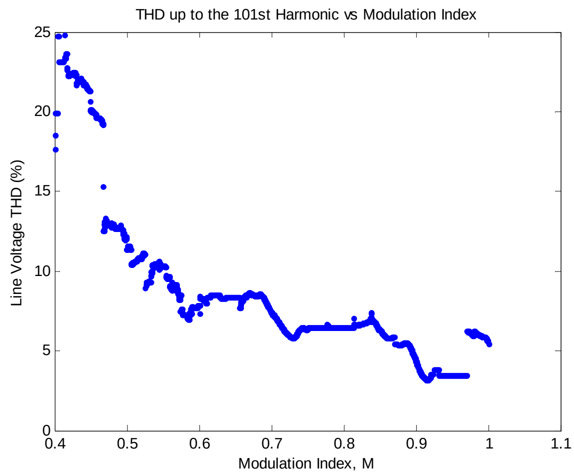

Fig. 7 Line voltage THD versus the modulation index

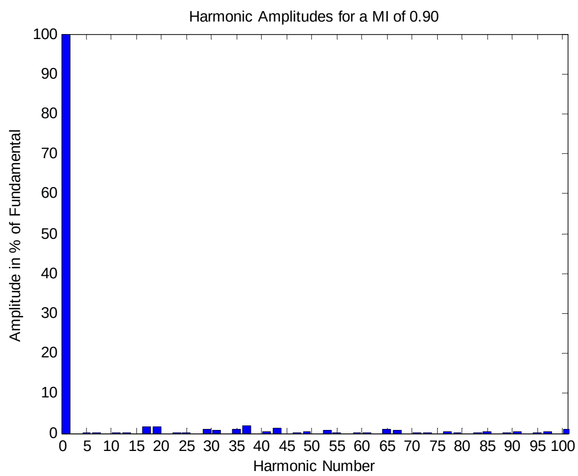

Fig. 8 Harmonic amplitude of 15-level inverter (Modulation index =0.90)

From simulation results, PSO is advantage for compute a large number of switching angles. The Modulation index between MI=0.8942 to 0.9653 are less than 5% or standard requirement. The best THD=3.191%, MI=0.9167. Fig. 8 show harmonic amplitude of multilevel inverter for modulation index = 0.90, THD=4.355% and all individual harmonics less than 3% or standard requirement. The possible switching angles are shown in Table III.

TABLE III
The Possible Switching Angles

MI	Switching Angles						
	α_1	α_2	α_3	α_4	α_5	α_6	α_7
0.9000	5.4290	13.0566	23.1152	33.8275	44.8734	61.5435	87.5856
0.9100	5.3895	12.4609	21.8352	32.8328	43.1988	60.5157	87.6340
0.9167	5.4562	12.0869	20.9360	32.2690	42.0065	59.7823	87.6846
0.9200	5.5156	11.9095	20.4677	32.0149	41.3811	59.3987	87.7106
0.9300	5.8124	11.5192	19.5382	31.6639	40.1300	58.6656	87.7759
0.9400	5.8419	11.5430	18.4354	31.5209	38.8489	57.9578	87.8528
0.9500	5.8419	11.5430	18.4354	31.5209	38.8489	57.9578	87.8528
0.9600	5.8419	11.5430	18.4354	31.5209	38.8489	57.9578	87.8528

VI. CONCLUSION

In this paper present advantage of both hybrid multilevel inverter and Particle swarm optimization for reduce harmonics. Hybrid multilevel inverter, which could create the number of level to 15-level and Particle swarm optimization (PSO) is the one of most artificial intelligent optimization techniques, it could find switching angles. Although many variables in system of equations. Number of harmonics are eliminated depend on number of equations or number of output levels. Therefore, the benefits of hybrid multilevel inverters could generated a many number of output levels and reduce switching devices including many harmonics elimination. For many equations problem, the artificial intelligent optimization techniques could be used instead the conventional methods. The simulation result are shown switching angle, THD versus the modulation index from 0.4 to 1.0. The THD under standard requirement at 5% at modulation index MI=0.8942 to 0.9653 and best THD is 3.191% for modulation index is 0.9167. Therefore, able to select the appropriate switching angles to achieve better performance of the inverter without filter.

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