Harmonic Improvement of Multilevel Inverter with Asymmetric Switching Modes and Harmonic Search Optimization Method

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Abstract

This paper deals with the harmonic analysis of multi-level converters and harmonic reduction methods. The proposed method for multilevel converter aims to provide a suitable model in an asymmetric switching mode and extract the analytical relationships for output harmonics. In the end, the harmony search optimization method is used to obtain the optimized output voltage harmonics in asymmetric switching mode. The proposed structure for the 5-level asymmetric inverter is presented using the results of the proposed model as well as the optimized harmony. Simulations are performed in Matlab 2018a software and the results show the total harmonic distortion (THD) reduction by about 17% and 28% for the proposed inverter.

Keywords: Multilevel Inverters, Harmonic Analysis, Modulation, Asymmetry in Switching

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1- Introduction

Using the power electronic equipment such as inverters has been popular today. Power electronic converters include dc-dc converters, ac-ac converters, rectifiers and inverters, among which the inverters are highly popular for their high power and high voltage industrial applications. Today, inverters with their wide range of applications are very important tools in industry and home applications and even in scientific research. Inverters are used in many applications such as drives, distributed generation systems, etc. The task of the inverters is to convert the direct input voltage to an alternating output symmetrical with the desired amplitude and frequency [1-3].

Inverters are found in different types and are utilized at various levels with different applications. Initial inverters were in the form of two-level inverters which due to their inefficiency in sensitive applications, including their use in medicine (due to the high harmonic distortion produced by these inverters and their low efficiency) were replaced by multilevel inverters which were introduced as a viable alternative and entered the market. [4-5]. By adding more levels to the multilevel inverter, the output voltage waveform quality improves. Ideally, if the number of levels tends to infinity, the total harmonic distortion (THD) of the output voltage waveform will approach zero. However, the maximum number of voltage levels is limited by factors such as the complexity of capacitor voltage balancing, the exponential increase of semiconductor devices to create more levels, the design difficulty, and the limitations of packing and circuit size. One of the significant advantages of multilevel structure compared to its two-level structure is that at the same switching frequency, the harmonic components of the multilevel inverter output waveform are lower [6-8]. Multilevel inverters have different types, three of which are Diode Clamped Multilevel Inverters, Flying-Capacitor Multilevel Inverter and Cascade Multilevel Inverters [9-10].

It is therefore highly desirable to develop methods for reducing harmonics and THD. Harmonic improvement in multilevel inverters can be investigated from various aspects [11]. Different structures of multilevel inverters have different output harmonic levels and can also vary significantly by changing the switching methods of output harmonic content of multilevel inverters. Switching methods are divided into two main switching and high frequency switching. In main frequency switching the output harmonics can be limited in two ways, the first being THD minimization, in which the switching angles are defined in such a way as to minimize THD. And in the method of removing low-order harmonics the switching angles are defined so that a number of low-order harmonics are eliminated depending on the number of converter levels. In both of these methods the main issue is the elimination of harmonics [12].

In this paper, multilevel chain inverter is used for unbalance analysis because it is modular and simple in structure and requires fewer elements than other multilevel inverter structures such as clamp diode structure and flying capacitor structure. For example, the conventional symmetric five-level chain inverter is shown in Fig. (13).

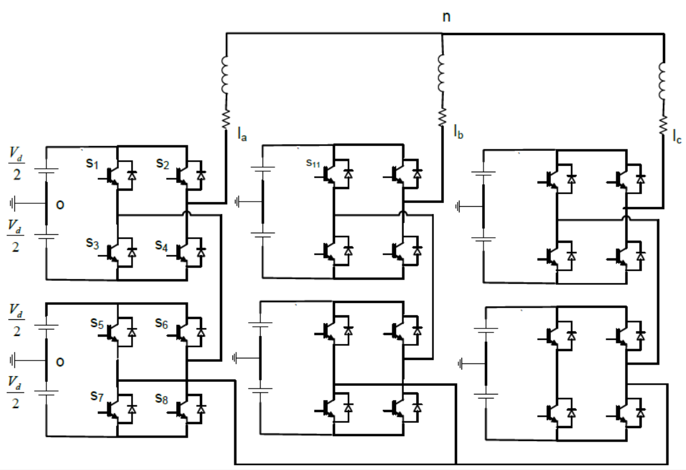


Fig. 1: Conventional symmetric five-level inverter chain structure

To obtain the conversion function, the inverter must be modeled first, and then the output variables expressed in terms of input variables. The output voltage and the input current of the multilevel inverter are as follows [13].

$$[V_{ab} \quad V_{bc} \quad V_{ca}] = TV_d \tag{1}$$

$$I_{in} = T[I_a \quad \mathrm{I}_b \quad \mathrm{I}_c] \tag{2}$$

In these relationships T is the inverter conversion function and V_{ab}, V_{bc}, V_{ca} are output voltages and I_{in} is input current and V_d input voltage and I_a, I_b, I_c are output currents. In the reference [14], the conventional PWM modulation method is used to obtain the output voltage of the symmetric inverter and investigate the harmonics. In the PWM modulation method, the pulse widths are variable, so the amplitude of the harmonics cannot be easily calculated. For this purpose, a new conversion function is defined in this reference that includes the effect of fire angle changes [14]. To obtain the modulation effect, the unmodulated waveform harmonic spectrum is subtracted from the modulated waveform harmonic spectrum [15]. The Fourier expansion of the symmetric five-level inverter output voltage according to Fig. (1) consists of the sum of two waveforms $F_{M1}(t)+F_{M2}(t)$; Fig. (3) shows this sum:

$$\begin{aligned}
&F_a(t) = F_{M1}(t) + F_{M2}(t) = \\
&V_{dc}\left(\frac{2}{\pi}\sum_{m=1}^{\infty}\left((-1)^m - 1\right)\frac{\sin(m\omega_0 t)}{m}\right) + \frac{2}{\pi}\sum_{m=1}^{\infty}\left(-\frac{J_0(mb)}{m}\sin(m\frac{\pi}{2})\right)\cos\left(m\omega_0(t-\frac{\pi}{\omega_0})\right) - \\
&\frac{2}{\pi}\sum_{m=1}^{\infty}\sum_{m=1}^{\infty}\frac{J_n(mb)}{m}\cos(nk\omega_0 t + n\delta_k))\left[\sin\left(m\omega_0(t-\frac{a_1+a_2}{2\omega_0})-\frac{n\pi}{2}\right)\cos\left(\frac{m(a_2-a_1)}{2}\right)\right] + \\
&\sin\left(m\omega_0(t-\frac{2\pi-a_1-a_2}{2\omega_0})-\frac{n\pi}{2}\right)\cos\left(\frac{m(a_1-a_2)}{2}\right) - \sin\left(m\omega_0(t-\frac{2\pi+a_1+a_2}{2\omega_0})-\frac{n\pi}{2}\right)\times \\
&\cos\left(\frac{m(a_2-a_1)}{2}\right) - \sin\left(m\omega_0(t-\frac{4\pi-a_1-a_2}{2\omega_0})-\frac{n\pi}{2}\right)\cos\left(\frac{m(a_1-a_2)}{2}\right)
\end{aligned} \tag{3}$$

For the analytical investigation of the asymmetric output harmonics in the switching mode, the symmetric mode also operates except that S1 is switched on from the first cell of phase A instead of α_1 in α_1' and the switch S_{11} is switched on from the first cell of phase B instead of α_2 in α_2'. Both of these changes are applied to the $F_1(t)$ phase A and B and the final changes are seen in line voltage [14].

Various modulations are used to generate the desired output voltage in multilevel converters. There are also different categories for these modulations. At the beginning of the discussion we should note that we must distinguish between different modulation methods and different control methods. Modulation in inverter means generating the average output voltage proportional to the reference wave given by the external algorithm. While controlling multilevel converters means applying the output voltage calculated by themselves [16]. The modulation of multilevel converters is generally classified according to their switching frequency [17]. There are three general categories to which frequency modulation is based, which are Fundamental Switching Frequency modulation, hybrid Multilevel switching frequency modulation, and High Switching Frequency Modulation.

The purpose of this paper is to investigate the harmonic effects of multilevel converters and harmonic reduction methods. Therefore, for the analytical investigation, a suitable model for multilevel inverters is considered and this model will obtain analytical relationships for output harmonics in cases such as asymmetry in switching and ripple in the input voltage. Using these analytical relationships, the output harmonics will be accurately calculated, and using these analytical relationships will provide a way to reduce the output harmonics in the asymmetric switching mode. Also in this paper in case of uneven input voltages, the selective switching method is applied to the multilevel inverter and the switching angles will be calculated using Harmonic Search (HS) optimization or method. This research is based on four sections. In the second part, definitions and literature review are presented, and in the third part the proposed method is outlined and the related relationships are described. The fourth section also shows the full implementation of the proposed method and the simulation results in MATLAB software.

2- Literature Review

Today, many advances have been made in all different fields of science [18-19]. The main purpose of static power converters is to generate the ac output waveform of a dc power supply. For sinusoidal ac output, size, frequency and phase must be controllable. Depending on the type of ac output waveform, these topologies can be considered as voltage source inverters where the controlled ac output is independent of the voltage waveform. There are other inverters that are designed as current modes and the ac output is controlled by the current waveform. Multilevel inverters have been the focus of attention in the electricity industry in recent years. This is due to the high voltage and power output at their outputs, as well as the use of low rated power electronic devices and the use of low voltage power supplies.

Multilevel inverters produce a smaller amplitude sinusoidal voltage with greater amplitude and a smoother waveform by series of smaller dc voltages. In general, the greater the number of these voltage sources, the larger the output window and the smoother the waveform, the greater the cost and complexity of control. In some cases, where power and voltage are not very much needed but a smoother waveform is required, increasing resources will not be cost-effective. Numerous methods have been proposed for switching multilevel inverters, some of which are discussed below [20].

Citarsa et al. have proposed a way to reduce harmonics in multilevel inverters. They have used step modulation because of the low switching frequency and the least wasted switching method. The proposed method has been applied to quadrupole and quadrupole inverters and from comparison of the Fourier analysis it was found that many harmonics have been eliminated by this method [21]. Prasad Panda et al. have investigated the elimination of harmonics in multilevel inverters by the optimal synchronous modulation method. In this reference, cascade inverters with identical and non-identical dc sources are investigated. The purpose of this paper is to present a new formula for the problem of selective harmonic elimination in multilevel inverters. Finally, they also use the FSO optimization algorithm to calculate the optimal switching angles needed to control the switching power supply [22].

Output voltage harmonics have been considered in a limited window in non-ideal states, and there has usually been no thorough and analytical investigation of these states. Here are some of these references. Tri Do et al. investigated the space vector modulation method for a conventional three phase inverter in [23]. This reference describes the switching vectors, the diagrams of the spatial modulation method, the work cycle matrices and the switching order, but no studies on the output harmonics have been performed. The effects of the unbalanced load on the output harmonics as well as the effect of the switching method presented on the output harmonics have not been investigated even with the simulation results. Cho et al. proposed the modulation method for multilevel chain inverters with asymmetric DC voltage sources [24] but in this case no harmonic analysis has been performed. In reference [25], Kangarlu et al presented a new structure for inverters under symmetric and asymmetric conditions. This five-level voltage structure produces fewer parts than symmetrical structures and has no imbalance problem.

In reference [26] Cho et al. investigated the control strategy for grid-connected inverters under asymmetric fault conditions. In this paper, current harmonics are investigated. Equations of current harmonics have been obtained and a method has been proposed for eliminating these harmonics but no discussion has been made on voltage harmonics. Nandhini et al. have presented a new topology of H-bridge-based multilevel inverters for PV system with reduced switches. By increasing the number of levels in multilevel inverters, complete harmonic distortion (THD) can be minimized. This paper presents a 21-level topology with reduced number of switches and DC sources. The main purpose of this proposed ACMLI EMI control topology is to reduce total harmonic distortion using various PWM techniques as well as minimize power semiconductor switches over conventional multilevel inverters. In this paper, it has been demonstrated that the overall harmonic distortion of the proposed MLI topology output voltage is significantly reduced compared to conventional inverters [27].

Nalcaci et al. presented a paper entitled "Selective Harmonic Elimination for Three Phase Voltage Source Inverters Using Whale Optimization Algorithm". In this paper, a whale optimization algorithm (WOA) is implemented to decide the optimal switching angles for a three-phase voltage inverter (VSI) to eliminate some of the high harmonics while providing the required voltage. In addition, the PSO optimization algorithm is also applied and the optimal switching angles for eliminating harmonics 5, 7, 11, 13, 17 and 19 are calculated. The output voltage resulting from the use of WOA and PSO is compared using full harmonic distortion (THD). Comparing these results, it has been shown that WOA yields faster and more accurate results in terms of THD reduction than the PSO algorithm in SHE applications [10]. Duranay et al. have presented a paper entitled "Intensive Learning Machine based on Selected Harmonic Eliminators for Single Phase Inverter". In this study, a new system is proposed to remove selected harmonics in single phase inverters. The modulation index is used as an input to the extreme learning machine and the switching signals are generated. The simulation was performed using Matlab/Simulink and verified with the tested results. It has been shown that the selected harmonics are removed from the load current and voltage for each given modulation index [26].

3. The Proposed Method

As we know with the growing use of inverters in the industry, the need to obtain more sinusoidal and harmonic output in inverters is felt more, especially in high voltage, and high voltage applications provide multilevel step inverters. It has been important in this respect, but the papers on harmonics in inverters, especially multilevel inverters, have addressed this issue in a limited way, especially the discussion of multilevel inverter harmonics in unnecessary situations. This paper aims to investigate these issues.

For harmonic analysis of the inverter, we must first model it. In order to model the inverter, its conversion function must be obtained. In this modeling, the inverter is modeled by its conversion function, which defines the output variables in terms of input variables. Finally, after determining the relationships of the input and output variables, the conversion function consists of the Fourier expansion of the switching functions. In order to optimize the harmonic evaluation of multilevel inverters after modeling we arrive at a general relation that is proposed for the selective elimination of harmonics for multilevel chain and modular converters. In this respect, the values of DC sources are considered as variables, thus increasing the degree of freedom compared to conventional methods. The elimination of low-order harmonics and THD minimization are achieved by optimally selecting switching angles and DC sources values. The HS optimization method is used to solve the nonlinear equations obtained. This method has high convergence speed, high accuracy and simplicity of application compared to other optimization methods. Different modulation methods such as PWM method and spatial vector modulation method have been proposed for multilevel inverters. One method of choice for these inverters is the selective elimination of harmonics. In this method, the circuit equations are obtained to obtain suitable switching conditions for eliminating low-order harmonics and minimizing THD, and then the obtained nonlinear equations are solved. Among the various modulation modes, only the selective elimination method of harmonics is capable of completely eliminating low-order harmonics.

Multilevel inverters have different modulator-based structures that have the lowest number of elements compared to diode clamp and capacitor structures. In [29] and [30], the analytical relationships of the output voltage harmonics of the multilevel inverters are given. Using the PSPWM modulation method and if N is a series inverter in each phase having a switching phase shift of $\text{ɗ} = \frac{(i-1)\pi}{N}$ relative to each other where i is the inverter i[th]. The phase voltage harmonics will be as follows.

$$v_{an-c}(t) = 2V_{dc}MN\cos\omega_0 t + \frac{4V_{dc}}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty \\ n\neq 0}}^{\infty}\frac{J_{2n-1}(2mM\frac{\pi}{2})}{m}\cos\left(\pi\left(m+n+1\right)\right)$$
$$\times\sum_{i=1}^{N}\cos\left(2m\left[\omega_c t + \frac{(i-1)\pi}{N}\right] + (2n-1)\omega_0 t\right) \quad (4)$$

This is achieved by simplification as follows:

$$v_{pn}(t) = V_{dc}\begin{bmatrix} 2MN\cos\omega_0 t + \\ \frac{4}{\pi}\sum_{m=1}^{\infty}\sum_{\substack{n=-\infty \\ n\neq 0}}^{\infty}\frac{1}{m}\cos\left(\left(Nm+n+1\right)\pi\right)J_{2n-1}(2Nm\frac{\pi}{2}M)\cos\left(2mN\omega_c t + (2n-1)\omega_0 t\right)\end{bmatrix} \quad (5)$$

In this respect M is the modulation index and J is the Bessel function of the first type. Given this relation only harmonics are the harmonics around the 2N coefficients of the carrier wave frequency.

3-1- Optimization Method for Modular Inverters

Modular multilevel inverters are suitable for use at high voltages and are easily expandable [31]. Compared to other converters, modular inverters have lower switching frequency and lower switching losses. Also, each inverter switch is switched on and off only once in the main period. The output voltage of the inverter is small steps so the inverter has small dv/dt and low harmonic distortion [32]. In these inverters all sub-modules are connected in series so the output voltage of the inverter is the sum of the output voltage of all sub-modules; The number of output voltage levels is 2S+1, with 2S being the number of modules in lower and upper arms. To calculate THD, we proceed as follows. The voltage of phase A is considered as follows.

$$V_{an} = S.V_{dc} - v_{au}$$
$$V_{an} = -S.V_{dc} + v_{al} \quad (6)$$

In this relation:

$$v_{au} = \sum_{i=1}^{2s} v_{aui} \qquad v_{al} = \sum_{i=1}^{2s} v_{ali} \quad (7)$$

The Fourier expansion is the output voltage of a modular multilevel inverter with the same DC sources as the relationship (8).

$$V_{out} = \sum_{n=1,3,...}^{\infty} \left[\frac{4V_{dc}}{\pi} \sum_{k=1}^{s} \cos n\theta_k \right] . \frac{\sin n\omega t}{n} \quad (8)$$

The following relationships must be solved to regulate the main component of the output voltage and remove the low-order harmonics.

$$\begin{aligned} &\cos(\theta_1) + \cos(\theta_2) + ... + \cos(\theta_S) = \frac{S\pi}{4} M_a \\ &\cos(5\theta_1) + \cos(5\theta_2) + ... + \cos(5\theta_S) = 0 \\ &\cos(7\theta_1) + \cos(7\theta_2) + ... + \cos(7\theta_S) = 0 \\ &\cos(11\theta_1) + \cos(11\theta_2) + ... + \cos(11\theta_S) = 0 \end{aligned} \quad (9)$$

Where the following condition should be true for this relation.

$$0 \le \theta_1 \le \theta_2 \le ... \le \theta_s \le \frac{\pi}{2} \quad (10)$$

Thus, THD is defined as relation (11) [31].

$$THD = \sqrt{\frac{\pi^2}{8} . \frac{S^2 - \frac{2}{\pi} \sum_{k=1}^{S} (2k-1)\theta_k}{\left(\sum_{k=1}^{S} \cos(\theta_k) \right)^2} - 1} \quad (12)$$

3-2- HS Optimization Method

The optimization problem raised is a nonlinear problem and must be solved numerically. Various methods have been proposed to solve this type of problem, which can include classical numerical problem solving techniques with modern optimization methods. Modern methods such as genetic algorithms have been proposed and developed to solve the disadvantages of classical methods. After the genetic algorithm, several other methods have been proposed to reduce computational time and improve the quality of the response obtained.

HS optimization method is provided by Geem which uses a similar method to the music making process. This method has been successfully applied to various optimization problems such as hydraulic parameter optimization and so on [34-36] In the making of music, the best mode (best harmony) is searched as in the optimization problem the best (optimal point) is searched. Harmonic quality improves step by step, just as the optimal response quality improves after each iteration. The HS method has the advantage that it can be used to solve continuous and discrete problems. It also uses random search, so derivative information is not needed and uses fewer parameters than the genetic algorithm method and does not require overlapping information of two adjacent vectors [37]. It is faster and more efficient than the PSO method and has the advantages of high convergence speed and accuracy compared to other optimization methods [38]. So with this method the problem can be solved faster, more accurately and with simpler formulations. The steps of the HS optimization method are as follows [34].

Step 1: Determine the initial values of the problem and the parameters of the algorithm.

The optimization problem is illustrated as follows:

$$\begin{aligned} &Minimize \quad f(x) \\ &x_i \in X_i \qquad i = 1, 2, \ldots, N \end{aligned} \tag{13}$$

In this respect f (x) is the objective function, Xi is the problem variable, N is the number of variables, and Xi is the allowed window for the value of the variables.

Step 2: Consider the harmonic memory.

In the second step, the Harmony Memory (HM) matrix returns with random values. The size of this matrix is equal to the harmony memory size (HMS). In this step the HM is initiated with random values of V_i and θ_i and then the initial conditions are checked.

Step 3: In this step a new harmony vector is created.

New harmonic vectors $x' = (x1', x2', \ldots, x_N')$ are constructed according to memory constraint rules, pitch setting and random selection.

The limitation of memory is that the value of the first variable x_1' of the new vector is determined from the specified values of HM. Other values of the variables can be similarly any of the corresponding values in HM. Conditions should be checked for new V_i and θ_i. If V_i and θ_i do not meet these conditions, new values are assumed. The HMCR parameter varies between zero and one and is the ratio of selecting a value from the values stored in the HM. Each value obtained in this section is tested according to the pitch value intended.

Step 4: Improve the harmony memory.

If the new harmonic vector $x' = (x1', x2', \ldots, x_N')$ is better than the worst of the previous harmonic vector in the harmonic memory and no other vector in the harmonic memory, The new harmony is placed in the memory of the harmony and the worst case is removed.

Step 5: The algorithm's stop conditions are checked.

Steps 3 and 4 are repeated until the stop condition is reached (reaching the number of duplicated repeats).

4. Simulation Results

The structure of the proposed inverter is shown in Fig. (2). In this paper, the proposed modulation method of SPWM for switching is used for the proposed inverter. Fig. 4 shows the structure of each module and the method of calculating its harmonics in the proposed inverter. The structure of the proposed modulation is also shown in Fig. (4), the parameters of this inverter being considered in accordance with Table (1).

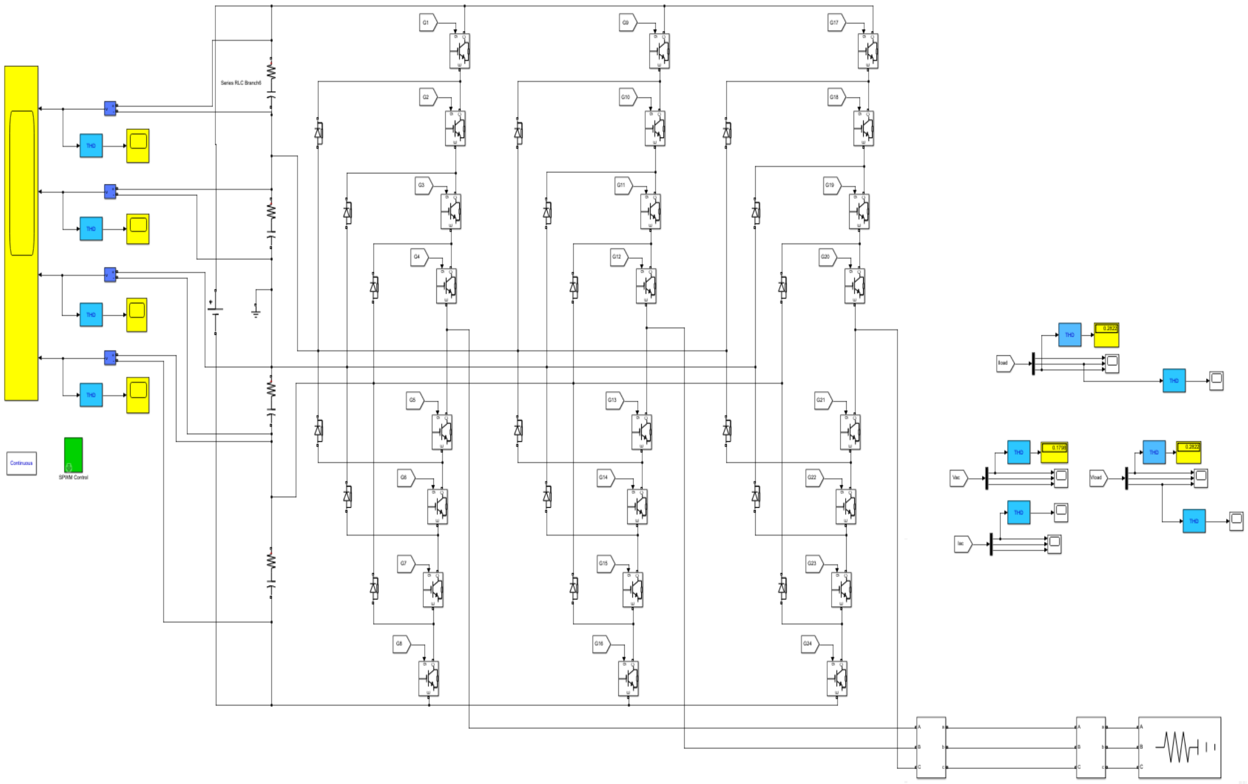


Fig. 2: The proposed 5 level converter

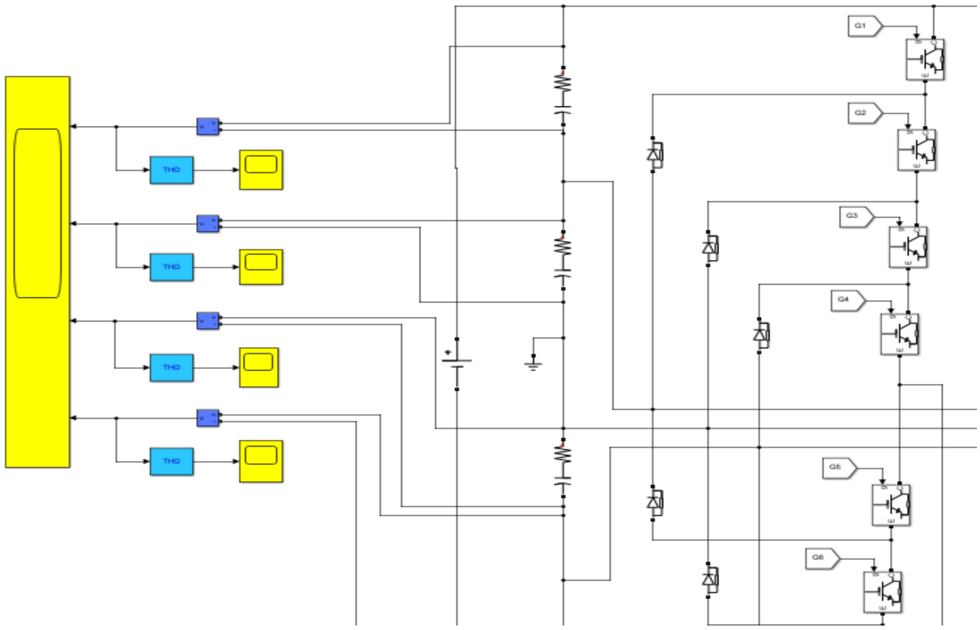


Fig. 3: The structure of each module and the method of calculating its harmonics

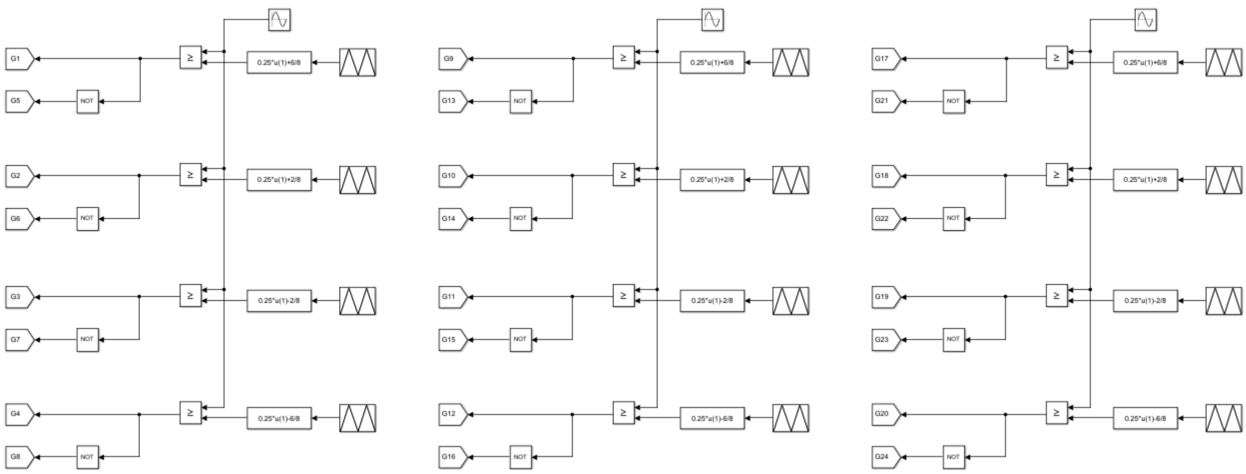


Fig. 4: The proposed SPWM modulation structure

Table 1: the proposed 5 level converter parameters

Values	Parameters
0.9	M
V5	V_d
90 degrees	Phase shift
50 Hz	Reference phase

	frequency
1000 Hz	Carrier wave frequency

This simulation is also done for 9-level inverters and so on. After performing the simulation in Matlab environment three-phase output voltage is shown in Fig. (5) for 5-level inverter and in Fig (6) for 9-level inverter. Is. It should be noted that in this method the carrier signals have a 90-degree phase shift.

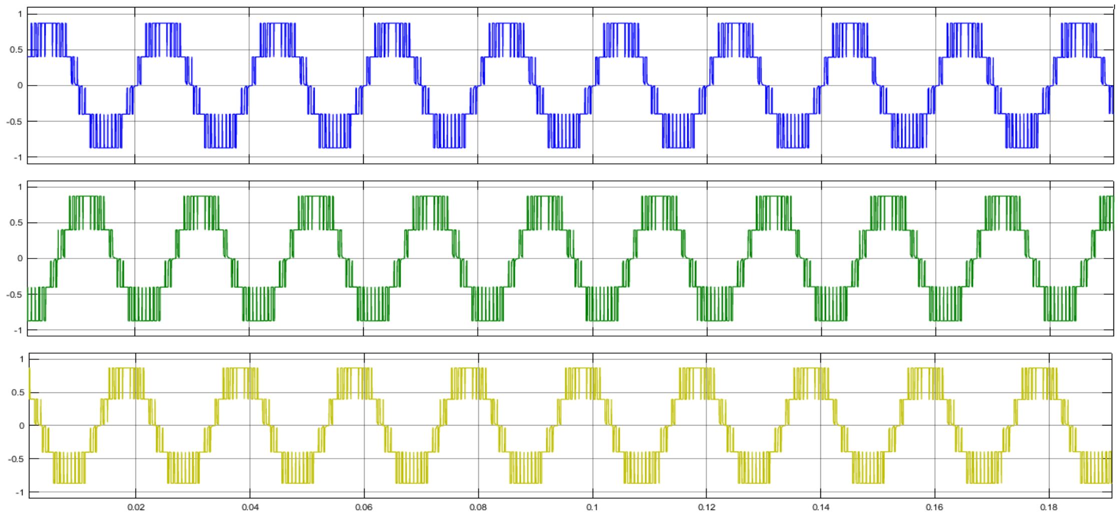


Fig. 5: Proposed output voltage of 5-level inverter with different phase shifts

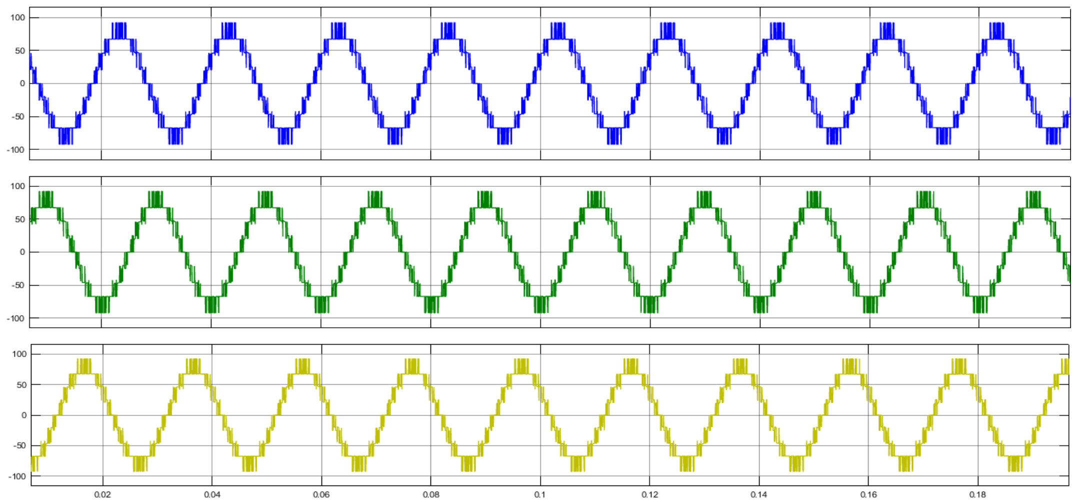


Fig. 6: Output voltage of the proposed 9-level inverter with different phase shifts

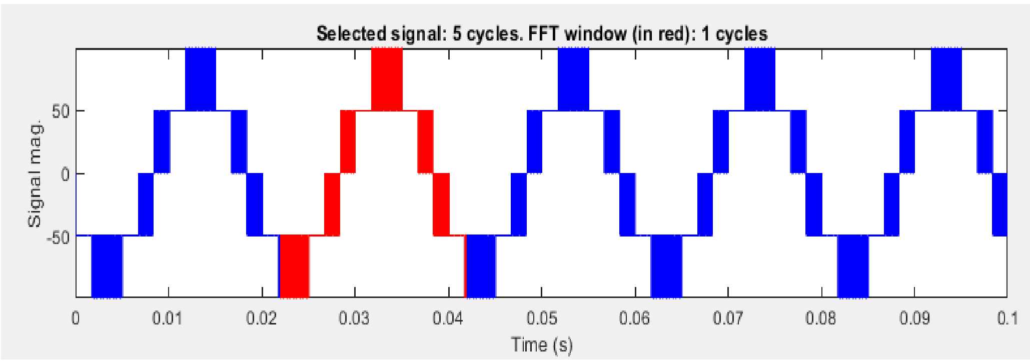
The THD corresponding to the AC voltage of the outputs optimized by the harmonic method for the inverter is measured and their results are presented in Table (2).

Table 2: THD values of inverter voltage output

Values	Parameters
0.1798	V_{ac} the out put of each branch
0.2822	V_{ac} load

4-2- Computing Harmonics by Calculating the Switching Angles

In the SPWN method, for each of the three inputs that are 90 degrees apart (the value of 90 degrees is considered in this paper), the optimal harmonic calculation is performed using the difference of the switching angles with the three inputs. By analyzing FFT, extraction of THD based on working frequency is shown in Figures 7 and 9. It should be noted that the analyzed frequency window is from zero to 5 kHz; To begin with, we must first consider a cycle of the first inverter signal and choose a band according to Figure (7). It can be seen from Fig. 7 that a cycle is identified and separated in red from 0.02 to 0.042 seconds and FFT analysis is performed. After FFT analysis, the THD value was 16.83%, which indicates that the optimized results are optimized by the proposed method.



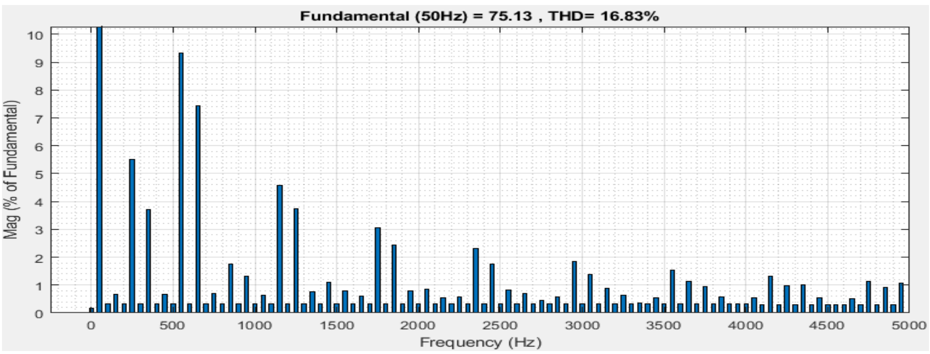


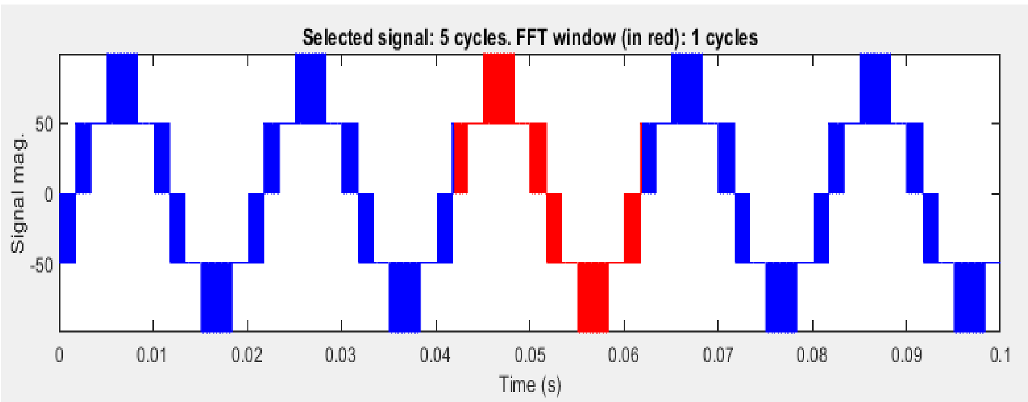
Fig. 7: Diagram of calculating a cycle from the first 5-level inverter signal and calculating THD at the input frequency of 50 Hz

As can be seen in the figure, the dominant harmonics are scattered around the Harmonic 10 and the paired harmonics are too low or zero and only individual harmonics are available. The dominant harmonics illustrated in Fig. (8) are presented for better consideration in Table (3). Since the reference wave frequency is 50 Hz and the carrier wave frequency is 1000, the dominant harmonics are scattered around the 8fc frequency.

Table 3: The proposed five-level inverter dominant harmonics

Harmonic order	Harmonic domain (%)	Harmonic frequency
3	10	$8f_c-7f_0$
5	0.8	$8f_c-5f_0$
7	5.5	$8f_c-3f_0$
9	3.8	$8f_c-f_0$
11	0.7	$8f_c+f_0$
13	9.3	$8f_c+3f_0$
15	7.5	$8f_c+5f_0$
17	0.6	$8f_c+7f_0$

In the following, consider a cycle of the second inverter signal and, according to Fig. (8), we must select a window. It should be noted that this signal has a phase difference of 90 degrees compared to the previous signal.



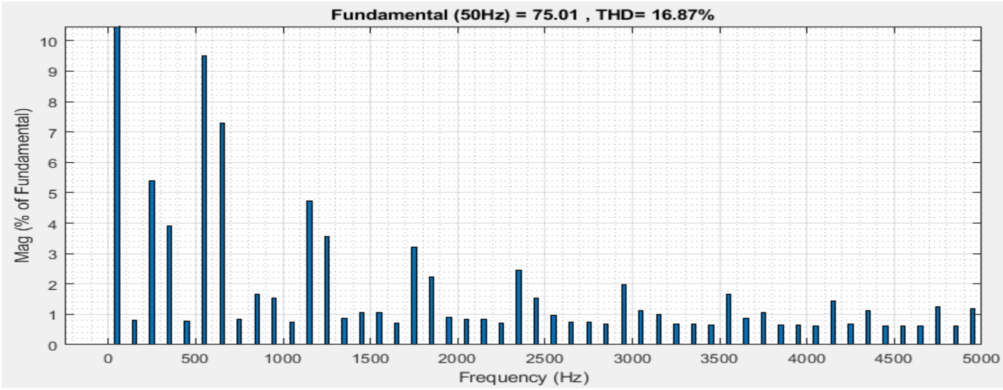


Fig. 8: Diagram of computing a cycle of the second 5-level inverter signal and calculating THD at the input frequency of 50 Hz

As shown in Fig. (8), it is observed that a cycle in the time window from 0.042 to 0.062 seconds is identified and separated by red and FFT analysis is performed in this window. Finally, consider a cycle of the third signal related to the inverter and choose a window according to Fig. 9. It should be noted that this signal also has a 90-degree phase difference relative to the previous signal.

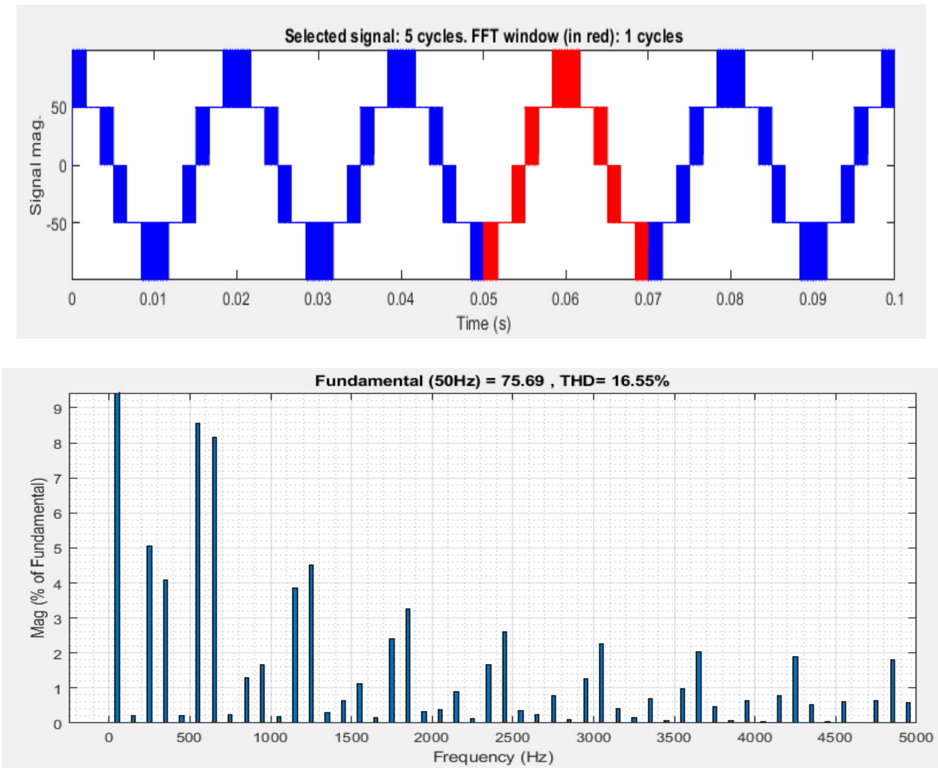


Fig 9: Graph showing the calculation of a cycle of the third 5-level inverter signal

As shown in Fig. (9), it is observed that a cycle in time window of 0.05 to 0.07 seconds is marked in red and FFT analysis is performed in this window. Considering the three input signals and their THD measurements, we observe that the THD value for all three inputs is approximately 17%, indicating the stability of the proposed structure and the proper performance of the switching angles.

Conclusion

The purpose of this paper is to investigate the harmonic effects of multilevel converters and harmonic reduction methods. Therefore, for the analytical study, a suitable model for multilevel inverters is considered and this model provides analytical relationships for output harmonics in cases such as asymmetry in switching. Using these analytical equations, the output harmonics are calculated precisely and by using these analytical equations, a method for reducing the output harmonics in asymmetric switching mode is presented. And switching angles were calculated using Harmonic Search Optimization or HS. The simulation results for the proposed asymmetric 5-level inverter show a significant reduction in THD at a switching frequency of 50 Hz. The THD also corresponds to the outputs of all three phases and the load outputs, respectively, and show 17 and 28 percent, respectively, which is very low for an inverter and for all harmonics.

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