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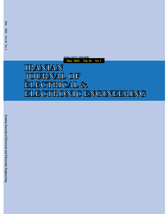

A Brief Review of Space Vector Modulation (SVM) Methods and a New SVM Technique Based on the Minimum and Maximum of the Three-Phase Voltages

H. Benbouhenni*, N. Bizon**(C.A.), and I. Colak*

Abstract: The space vector modulation (SVM) method was recently proposed and captured the interest of scientific research in the following years. In this paper, besides a brief review of the SVM methods proposed in the literature, a new SVM strategy based on the calculation of the minimum (Min) and maximum (Max) of three-phase voltages is proposed. The proposed SVM technique does not have to calculate the sector and angle, as is done in the traditional SVM technique. Therefore, it is the easiest technique to accomplish compared to the traditional SVM method and other existing methods. Compared with the traditional pulse width modulation (PWM), the advantage of using this new SVM strategy is that the scheme is simple and the total harmonic distortion (THD) value in the output of the two-level inverter is minimized. The technology has been simulated by MATLAB/Simulink, and then implemented on a real traditional two-level inverter using the dSPACE card. It is worth reporting the reduction obtained for THD using the proposed SVM technique (where THD is about 70%) compared to the traditional PWM technique (where THD is about 79.5%).

Keywords: dSPACE, Pulse Width Modulation, Space Vector Modulation, Total Harmonic Distortion, Two-Level Inverter.

1 Introduction

IN electrical engineering, the two-level inverter is widely used in command of alternative motor drives. The two-level inverter is an easy to implement and simple scheme compared to the multilevel inverter. However, the control of the two-level inverter is a simple algorithm. On the other hand, various modulation strategies have been proposed to control the two-level inverter. Most existing strategies widely used a traditional pulse width modulation (PWM) technique based on the comparison of two different signals, one is a triangular signal and the other is a sinusoidal signal. However, this method will generate more current and voltage ripples and harmonics (THD) in the outputs of the two-level inverter [1]. In [2], another PWM technique based on Neural Algorithms (NAs) has been proposed in which the hysteresis comparators of the traditional PWM technique are replaced by three NA-based schemes. This designed PWM strategy can minimize the THD value for the output voltage waveform.

There are several methods of PWM methods that have been proposed to improve the effectiveness of the traditional method. Among these methods, we find synchronous PWM [3], selective harmonic elimination strategy (SHES) [4], traditional space vector modulation (TSVM) method [5], carrier-based space vector PWM (CB-SVPWM) [6]. In [7], a new algorithm for the SVM for multi-level inverters has been proposed. This strategy is generated by triangulating the sector to a two-level sector in the space vector diagram

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* The authors are with the Department of Electrical & Electronics Engineering, Faculty of Engineering and Architecture, Nisantasi University, 34481742 Istanbul, Turkey.
E-mails: habib.benbouenni@nisantasi.edu.tr and ilhami.colak@nisantasi.edu.tr.
** The author is with the Faculty of Electronics, Communication and Computers, University of Pitesti, 110040 Pitesti, Romania.
E-mails: nicu.bizon@upit.ro.
Corresponding Author: H. Benbouhenni.
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and using the two-level SVM formulas. This proposed method does not require a lookup table like to traditional SVM technique. This designed SVM strategy is a simple algorithm compared to the traditional SVM strategy. The proposed SVM strategy can be extended to an n-level inverter, which is easy to achieve and suitable for high-voltage, high-power applications. The experimental results showed the effectiveness of the proposed method in reducing current ripples and the ease of its implementation. Another simple method suggested in [8], where this method is designed to control a multi-level inverter (MLI). However, the MLI switches are controlled by three different types of multi-carrier PWM (MC-PWM) techniques (alternate phase opposition and disposition (APOD), phase opposition and disposition (POD), and phase disposition (PD)). The designed methods were compared in terms of percentage harmonic distortion of current. In [9], three different SVM methods are proposed to improve efficiency and reduce switching losses in high power level induction motors. These ways are symmetrical modulation, two-phase modulation, and a technique obtained by a combination of both of the previous strategies. In [10], the active and reactive power ripples were minimized by using the SVM technique. The applied results showed the improved characteristics obtained for the designed strategy. In [11], the quasi-switching boost T-type inverter is controlled by the SVM strategy. The asynchronous motor was controlled by SVM technology [12]. This motor was fed by a Neutral Point Clamped (NPC) inverter. In [13], three modulation strategies, namely the nearest level modulation (NLM), the traditional SVM, and the phase-shifted sinusoidal PWM (PS-SPWM) technique, were compared with each other. By observing the results, we find that the SVM method gave very satisfactory results to both NLM and PS-SPWM techniques. Three dimensional SVM (3D-SVM) technique was proposed to control a 3-phase four-wire NPC converter [14]. This designed technique improves the quality of power compared to the traditional SVM strategy. In [15], the control of PV systems based on the SVM technique was proposed. Through the obtained results, we find that this system has improved its performance using the SVM method compared to the PWM method.

Some recently published papers deal with the implementation of the SVM method on a multi-level inverter and improving the effectiveness of control methods such as field-oriented control [16-20]. Most of these works have been experimentally verified. The study presented a comparison between the theoretical and experimental studies. In [16], the implementation based on the traditional SVM strategy of the five-phase VSI was proposed. In [17], the traditional SVM strategy was designed to control the medium and high-energy converters. In [18], a new single-phase grid-tied NPC five-level inverter was proposed based on the traditional SVM technique. A three-phase AC voltage source using sinusoidal PWM (SPWM) control is presented [19]. Field-oriented control technique and traditional SVM technique were combined to better control the permanent synchronous motor using the dSPACE controller [20]. The experimental results confirm how important the proposed method is in decreasing the value of THD.

Traditionally, the SVM techniques have gained importance in the recent past due to their superior modulation characteristics and fast response, although this modulation strategy is difficult to implement compared to the traditional PWM method. For example, it is worth mentioning that the SVM strategy reduces the harmonic and ripples of voltage and current compared to traditional PWM and other modulation strategies. The principle of the traditional SVM method is detailed in [21-24]. The main disadvantage of the SVM strategy is the fact that it requires the calculation of area and angle based on the space vector principle, so many improvements are recently proposed in the literature [25-33]. Among these methods used to improve the performance and effectiveness of the SVM method, we find neural networks, and this is due to its advantages compared to the rest of the methods of artificial intelligence, for example, fuzzy logic. Accuracy and speed are the two main features of neural networks. In [25], a new SVM method based on neural network control is proposed. Compared with the traditional SVM technology, the proposed neural SVM technique is robust and has a simple algorithm. In addition, this new SVM strategy reduces the harmonics of the voltage/current of a two-level inverter [26].

Several papers analyze and propose changes to this new SVM method for different applications [27-32], such as a five-phase quasi-impedance source inverter [27], asymmetrical six-phase drive [28], or a multilevel converter [29]. Since SVM strategies that are improved based on neural networks and fuzzy logic are proposed in [30] and [31] respectively and applied to control of a doubly-fed induction generator [32]. In [33], a new SVM technique based on nearest level modulation (NLM) is presented. This proposed method was applied to both traditional, three-level, and five-level inverters. The numerical simulation results showed the robustness of the proposed method.

In this work, in addition to a brief review of the SMM methods proposed in the literature, a new scheme of the traditional SVM strategy was designed and implemented to control traditional inverters by using dSPACE® (a dSPACE GmbH product). As you know, the classic SVM method has been suggested in several scientific works [34-36]. The disadvantages of this traditional SVM method are explained in the work [36]. In this work, a proposed SVM method of the classical SVM method will be implemented for its verification.

The main objective of this work is the implementation of a new SVM technique based on the Min value and Max value of 3-phase voltages (V_1, V_2, V_3) to reduce the current and voltage ripples of the traditional inverter. In this proposed method we radically changed the traditional method to have a simpler method that can be easily applied to the multi-level inverter. So, this proposed SVM strategy has a simpler algorithm, it is a robust technique, and its application results in lower conversion losses compared to the traditional SVM technique. The fast dynamic response is another key advantage of the proposed SVM method. To validate the performance mentioned above, the proposed SVM technique was implemented using dSPACE.

Thus, the novelty of the research study are as follows:

- A brief review of the recently proposed spatial vector modulation (SVM) methods in the literature is presented.
- A new SVM strategy is designed to provide better efficiency to the traditional inverter while maintaining the advantages of the traditional PWM strategy, which are robustness and low voltage fluctuations; it is worth mentioning that the proposed SVM technique does not have to calculate the sector and the angle, as is done in the traditional SVM technique, resulting in increased simplicity in implementation.
- The performance of the proposed SVM technique is compared to the traditional PWM strategy and other reference strategies from the literature.

The theoretical and simulation study of the modified SVM method is validated by the experimental results obtained.

The rest of the work is organized as follows. State-of-the-art of space vector modulation (SVM) methods proposed in the literature are presented in Section 2. Section 3 gives an overview of the traditional inverter. Section 4 includes a detailed overview of the new SVM method proposed in this paper, highlighting the differences between it and the traditional SVM method. The numerical simulation results for the new SVM technique are shown and compared with the traditional PWM technique in Section 5. In Section 6, the experimental results using the dSPACE are presented and analyzed. The performance and advantages of the proposed SVM method are compared and discussed in Section 7. Finally, concluding remarks are given in the last section.

2 State-of-the-Art of the Space Vector Modulation (SVM) Methods

In the field of inverter control, there are two more widely used methods, namely PWM and SVM techniques. However, method PWM strategy despite its simplicity and ease of implementation provides unsatisfactory results compared to the SVM strategy. On the other hand, the SVM strategy provides very good results that it is difficult to achieve and is also characterized by the complexity of the algorithm, especially in the case of a multi-level inverter. This is not present in the case of PWM strategy, where PWM strategy can be used in the case of a multi-level inverter easily.

The main objective of the SVM strategy is to generate control sequences of the switches of the inverter allowing to generate an output voltage vector as close as possible to the reference voltage vector. This technique follows the following principles:

- Sampling of the reference signal at regular intervals T_e called the modulation period.
- Realization in each modulation period, of a pulse of width T, centered on the period and whose average value is equal to the value of the reference voltage in the middle of the modulation period.
- Standardization of the states of all the switches of the same half-bridge, in the center and at both ends of the period.

This modulation strategy is carried out in synchronism on the three phases. The three desired sinusoidal voltages at the output are represented by a single vector called the reference voltage vector.

There are seven main stages to the implementation of the SVM strategy in the case of the classic inverter, which is as follows:

- Determination of the reference voltage vectors V_α and V_β.
- Identification of sectors.
- Calculation of the variables X, Y, and Z.
- Calculation of T_1 and T_2 for each sector.
- Generation of modulating signals T_{a_on}, T_{b_on}, and T_{c_on}.
- Generation of the S_a, S_b, and S_c pulse series.

The reference voltage can be calculated according to the following relationship:

$$V^* = \sqrt{V_\alpha^2 + V_\beta^2} \tag{1}$$

Equation (2) represents the relationship between each of the V^*, T_1, T_2, and T_0.

$$V^* \times T_e = V_1 \times T_1 + V_2 \times T_2 + V_0 \times T_0 \tag{2}$$

where, T_2 and T_1 represent time (sec) widths of adjacent switching vectors V_2 and V_1, respectively, T_s is the total period time, and T_0 represents as time (sec) width of V_0 (zero vector).

Equation (3) represents how to calculate the angle of movement of a reference beam within any sector.

$$\theta = \arctan(\frac{V_\alpha}{V_\beta}) \tag{3}$$

where, θ represents the values sample of the V^* in different sector.

To calculate the total period time, the following equation can be used:

$$T_e = T_1 + T_2 + T_0 \tag{4}$$

where, T_1 and T_2 are calculated from projecting V^* position along α-axis and β-axis with respect to space vector diagram origin. On the other hand, the space vector diagram of the two-level inverter can be divided according to the position of V^* (either inside or outside the hexagonal space vector diagram) into two parts: Over modulation (where $M_a > 0.907$) and linear modulation (where M_a is 0.907).

According to [37], the following equations can be used to calculate both T_1 and T_2.

$$T_2 = T_s(\frac{V^s_{\beta 0}}{h}) \tag{5}$$

$$T_s = T_s\left(\frac{-V^s_{\beta 0}+V^s_{\alpha 0}}{2h}\right) \tag{6}$$

From (5) and (6), T_0 can be easily calculated.

To use this method in the case of a multi-level inverter requires complex calculations. In the case of a multi-level inverter, this method is called the multilevel SVM technique. As it is known, the application of the SVM method is complicated and difficult in the case of a multi-level inverter, especially in the case of a 5 and 7-level inverter. In this case, the dynamic response speed is slowing down. Moreover, the cost of completion doubles, and this is undesirable.

In order to facilitate the use of the SVM technique in the case of a multi-level inverter, several methods are suggested in [38-41]. In the case of a multi-level inverter, complex mathematical equations are needed in order to determine the position of V^* and also to calculate the angle of position. On the other hand, the complexity lies in the number of space vector diagrams in the case of a multi-level inverter, wherein in the case of a three-level inverter, there are 2 out of the space vector diagram. To avoid this complexity interesting techniques have been designed in the literature to minimize the complexity to implement multilevel SVM technique with reasonable reflective performance.

In a multilevel inverter, there are 6 sectors (S_i = 6) in the case of the n-level space vector diagram. The switch states of the n-level space vector diagram can be calculated by n_3. On the other hand, the switching vector for any level of multilevel is categorized into the short vector (SV), zero vector (ZV), medium vector (MV), and large vector (LV). Also, the switch states are written as (a b c). Table 1 is a comparative study between several types of multi-level inverters in terms of the number of switch cases, sector, harmonic distortion of current, quality of current, number of space vector diagrams, and number of sub-triangle.

From this table, we can see that the complexity of the reflector increases with the number of levels. However, the quality of the current increases with increasing levels.

The three-level inverter is the most widely used in the field of controlling electrical machines than the rest of the other types of multi-level inverters, because of its ease of implementation and the quality of the current obtained. Fig. 1 represents the method or steps necessary to accomplish the three-level SVM technique. By observing this picture, we find that the three-level SVM technique in the case of a three-level inverter is complex and requires many calculations. It is also difficult to achieve theoretically and practically, and this is undesirable.

In order to complete the three-level SVM technique, several stages are required, which are shown in Fig. 1, which makes the response speed in this case slow.

To remedy this drawback, we propose here another SVM modulation technique. The proposed method is very simple and easy to perform in practice. The principle of the latter consists in calculating the minimums (Min) and maximums (Max) of the rotor voltages. This proposed method will be explained in Part 4 of this work.

3 Two-Level Inverter

In recent years, two-level inverters are becoming more popular in electronic systems. For an application such as control machines and power wind. The main advantage of the two-level inverter is a control easy to implement, a simple modulation technique, and a simple structure compared to the multilevel inverter. Fig. 2 shows the scheme of the traditional two-level inverter. Through this figure, the inverter structure comprises two DC voltage sources and six switches (usually implemented using IGBTs and the anti-parallel diodes) [42]. The two-level inverter can be used for any type of resistive-inductive load. The two-level inverter can produce two levels at the output line voltage waveform. Table 2 shows the switching states of a two-level inverter and the generated levels for the phase and line voltage.

In order to control the inverter, there are several methods suggested in this field. Among the most famous of these methods, we find PWM technique and

Table 1 Comparative study between several types of multilevel inverter.

Level of Multilevel inverter	Number of sectors	Switch states	Number of space vector diagram	Number of sub-triangle	Quality of current	Harmonic distortion of current
Three-level	6	27	2	24	Acceptable	High
Four-level	6	64	3	36	Good	Medium
Five-level	6	125	4	64	Very good	Low
Sixe-level	6	216	5	100	Excellent	Low
Seven-level	6	343	6	144	Excellent	Very lew

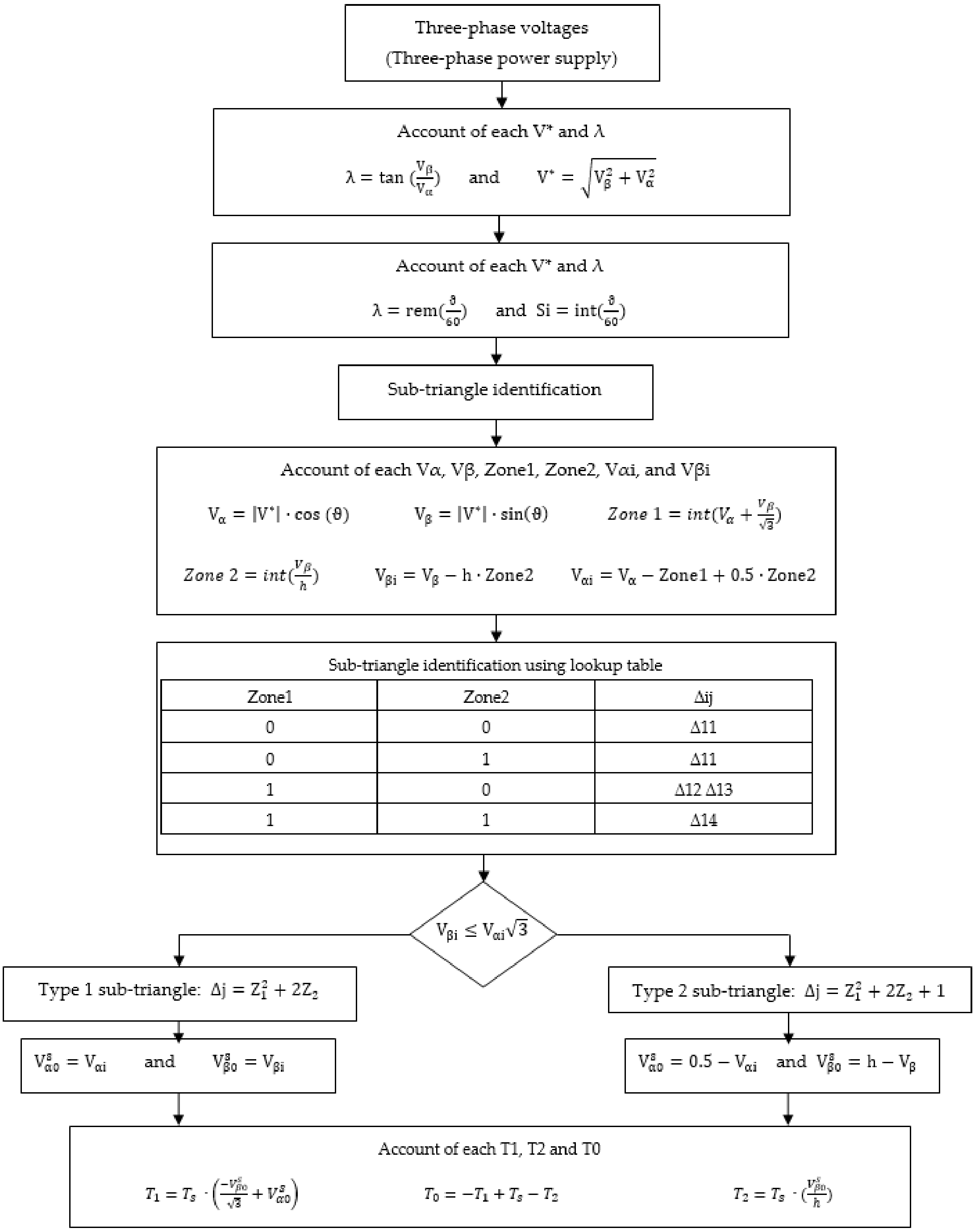


Fig. 1 Flowchart of three-level SVM technique.

traditional SVM strategy. Similar to these methods, there are other smart methods used to control the inverter such as neural PWM strategy and neural SVM technique. The obtained results confirmed that the intelligent modulation techniques are much better than the traditional modulations strategies in terms of underestimating the value of THD.

The output phase voltages, in terms of the switching functions, are:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \tag{7}$$

Table 2 The switching state of the two-level inverter.

State	On and off switches						Output voltage	
	S_1	S_2	S_3	S_4	S_5	S_6	V_a	V_{ab}
1	0	0	0	1	1	1	0	0
2	1	0	0	0	1	1	+2E/3	E
3	1	1	0	0	0	1	+E/3	0
4	0	1	0	1	0	1	-E/3	-E
5	0	1	1	1	0	0	-2E/3	-E
6	0	0	1	1	1	0	-E/3	0
7	1	0	1	0	1	0	E/3	E
8	1	1	1	0	0	0	0	0

where, S_n are the upper switches. States and (n = 1, 2, or 3) are the phases of the inverter. V_n is the output phase voltage (n = a, b, or c).

Fig. 3 shows the voltages generated by the traditional inverter in the α-β coordinate system. For these spatial voltage vectors, there are a total of 8 vectors: two zero vectors (0, 7) and 6 active vectors (1, 2, 3, 4, 5, 6) in the α-β coordinate system.

Due to its simplicity and ease of implementation, the most used control method of the inverter is the PWM method. It is based on the comparison of two signals of different shapes and frequencies. For a PWM signal, we use a sine signal with a frequency of 50 Hz and a second signal that can be a triangular signal with a frequency much greater (about 50 times) than the frequency of the sine signal. The following figure shows the principle of obtaining a PWM signal (Fig. 4). Among the minuses of this method is that it gives large ripples of the electric current and a variable frequency at the output of the inverter. To overcome this problem and keep the structure simple, we are introducing a new method for SVM called modified SVM.

In part 4, we will try to give the concept and principle of this new method. We will also give a figure through which we explain the principle of the work of this new method.

4 Proposed SVM Technique

Traditionally, the SVM techniques were based on space vectors, since the zone and angle are difficult to calculate by the reference voltage. These calculations are performed in the (α, β) complex plane based on the Clarke transformation of the three-phase voltage references (V_a, V_b, V_c). This strategy was proposed by Der Broeak in 1988. This classic method was used to control several electrical machines such as the asynchronous motor and the synchronous motor. In addition, it was used in the field of renewable energies and gave good results compared to the classical PWM method. Despite these results, there is a negative in using this method, which is the high cost of completion for the project of producing electric power from renewable sources, and this is due to the complexity of the classical SVM method. Fig. 5 shows the principle of the conventional SVM technique. It is shown that the implementation of the conventional SVM technique is difficult compared to the PWM technique or other strategies such as PWM, third harmonic injection pulse width modulation (THIPWM), digital pulse-width modulator (DPWM), and so on [43].

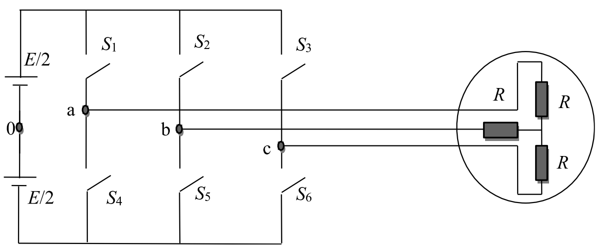


Fig. 2 Two-level inverter.

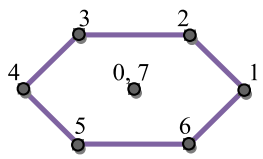


Fig. 3 Voltage generated by conventional inverter.

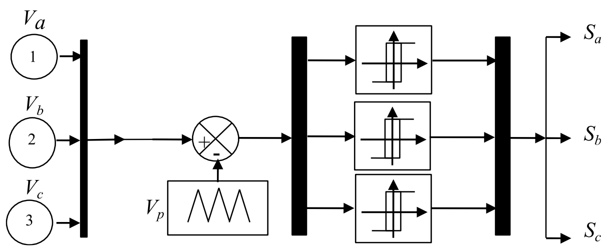


Fig. 4 Traditional PWM technique.

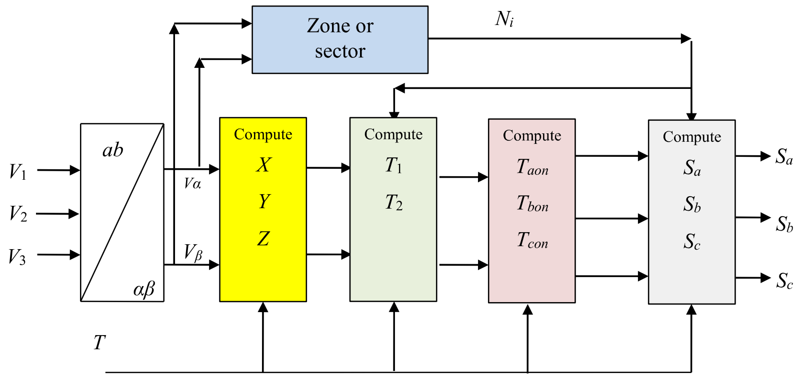


Fig. 5 Traditional SVM technique [43].

Despite these many advantages, the conventional SVM technique method still provides a great value for current ripples, and this is the main disadvantage that characterizes it [34-36]. But this disadvantage can be overcome by applying intelligent methods to this strategy [30-32], such as the neural networks [30] and fuzzy systems [31]. The latter is giving very good results in the field of electrical machine control [30, 32]. In this part, we designed a simple structure of the SVM technique based on the following steps:

- Calculate the minimum voltages, min(V_1, V_2, V_3)
- Calculate the maximum voltages, max(V_1, V_2, V_3)
- Find the switching states.

where the voltages (V_1, V_2, and V_3) in the SVM technique are calculated by using Max and Min technique.

Fig. 6 shows the structure of the modified SVM technique. Fig. 7 shows the hysteresis controllers. The basic principle of the new SVM technique will be detailed below.

The proposed modified SVM technique is a new technology presented in this work. This new modulation is very simple and does not require an electronics specialist. By comparing Figs. 5 and 6, we find that the proposed method is very simple compared to the traditional method. Also, the proposed method contains fewer electronic components compared to the traditional method, which makes it easy to implement in practice. This proposed method has a very simple operating principle and uses hysteresis comparators to select switching states (see Fig. 7). The principle of the latter consists in calculating the Min values and Max values of the energy source. This proposed method uses the trigonometric sign (V_p) to obtain switching states.

The principle of the proposed SVM technique is determined in four steps:

- Step 1: calculate Min of the energy source;
- Step 2: calculate Max of the energy source;
- Step 3: calculate the sum of Min (V_a, V_b, and V_c) and Max(V_a, V_b, and V_c);
- Step 4: generation of the S_a, S_b, and S_c pulse series.

To obtain the control signals (pulse series) of the electronic elements (transistors), we need hysteresis comparators. In the two-level modified SVM technique, we need three hysteresis comparators. In this work, we used the value 1 as a higher level for hysteresis comparators and the value 0 as a minimum level. A value of 1 indicates that the switch is running and a value of 0 indicates that it is in a shutdown state. On the other hand, we used the value 1/2 to get the average value of the sum Min values and Max values. Calculation of this value is of paramount importance in this proposed method which is to obtain almost the same principle as the traditional method. To obtain high durability and good efficiency, we used the value 0.5 to get a signal that represents the SVM technique.

This designed strategy is a robust strategy, easy to implement, and simple structure compared to the traditional SVM technique. Another positive aspect of this method is that it does not take up much memory space, unlike the traditional method, which requires memorizing the values of the sector and the angle. So, the cost of implementation for the modified SVM strategy will decrease. By comparing the traditional method with the modified SVM method, we find that the proposed method takes less memory space and low cost. Through these advantages, this modified SVM method will have an important soon in the field of electronics and the control of electrical machines.

Table 3 represents a comparative study between the proposed SVM method and the classical SVM method. Through this table, we conclude that the proposed SVM method is better than the classical SVM method, especially in the case of a multi-level inverter.

Through Fig. 6 we note that this proposed SVM method can be applied to multilevel inverters very easily similar to the traditional method. Also, by this proposed SVM method, the cost, size, and weight of the device can be reduced.

Due to the number of electronic elements contained in the proposed SVM method, which makes it provide a very fast response, unlike the traditional SVM method, which contains a greater number of electronic elements and the rapid response is a very important thing in the field of electronics and electrical machine control.

5 Simulation Results

To find out the efficiency of the proposed method in reducing the THD value of the electric current produced by the two-level inverter, we will divide this part into two parts, according to the type of load used. So that the first part of the load condition is resistance and the second part the load is RL.

5.1 First Part: Load R

Simulation of the modified SVM strategy for a two-level inverter is conducted by using MATLAB software. The simulation block diagram of the modified

Table 3 Comparative study between traditional and proposed SVM techniques.

Criteria	Traditional SVM technique	Proposed SVM technique
Simplicity	Complicated	Simple
Switching losses	Low	Low
Robustness	More robust	More robust
Speed of response	Slow	Fast
Implementation	Difficult	Easy
Completion cost	High	Low
Output voltage THD [%]	Low	Low

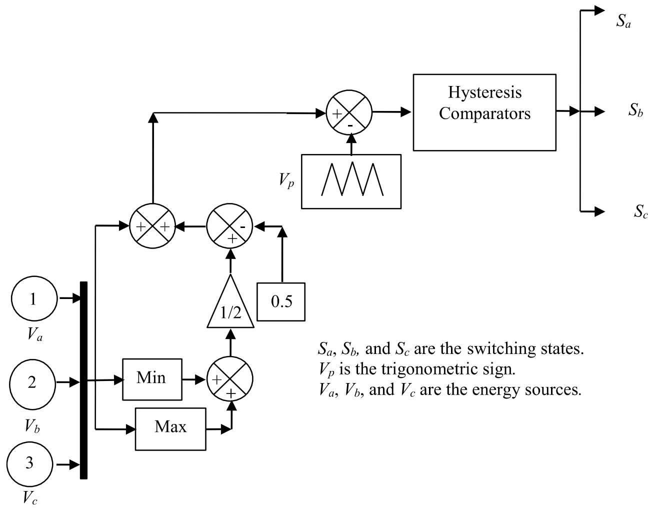


Fig. 6 Two-level inverter.

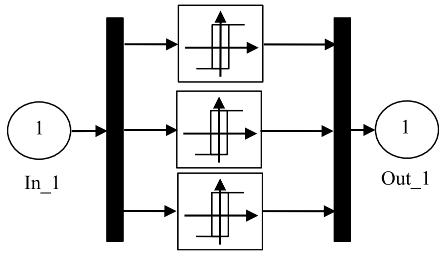


Fig. 7 Hysteresis controllers.

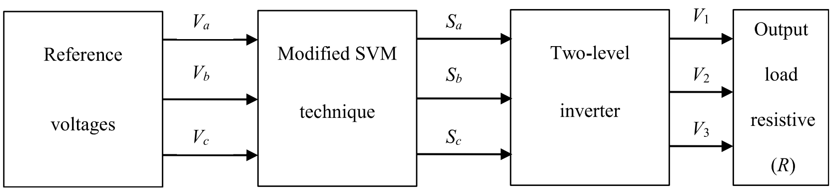
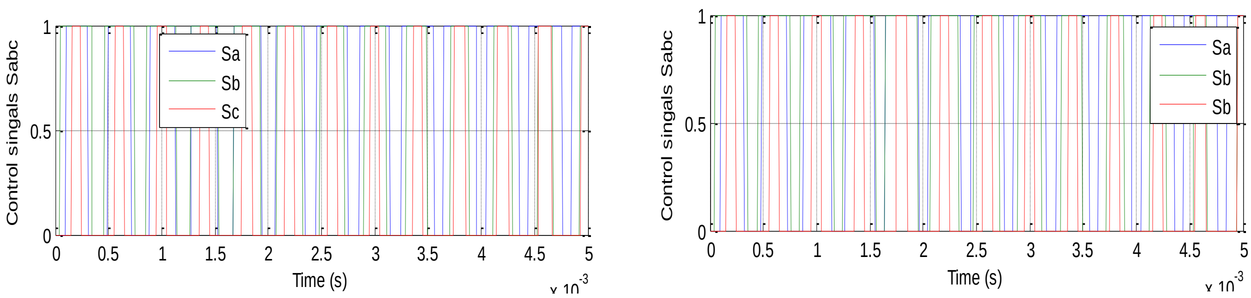


Fig. 8 Block diagram of the modified SVM for traditional inverter.

Table 4 Simulation values of THD for resistive load.

Techniques	THD value [%]		
	V_a	V_{ab}	I_a
PWM	79.49	79.49	79.52
Modified SVM	71.32	70.83	69.96



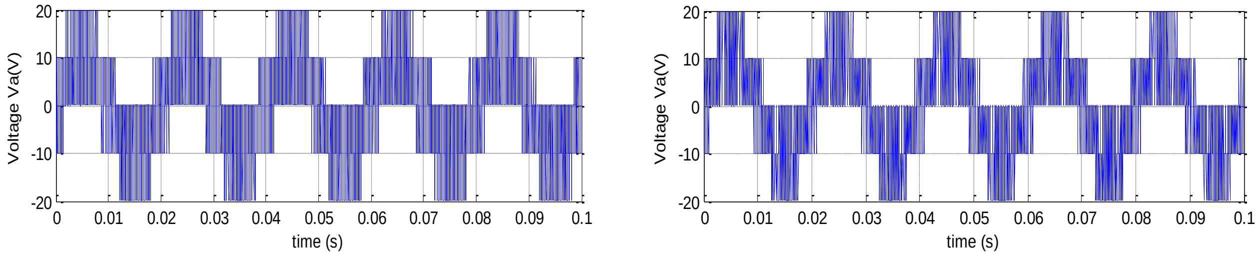
(a) (b)

Fig. 9 Control signals; a) PWM and b) modified SVM.

SVM method is given in Fig. 8. The modified SVM method is designed to minimize the ripple and harmonics of current and voltage of the traditional inverter. The following values are considered in the simulation: frequency of 50 Hz, output load is resistive with value $R = 100\ \Omega$, and DC voltage source has a reference value in the range of 20-35 V to compare the simulation and experimental results.

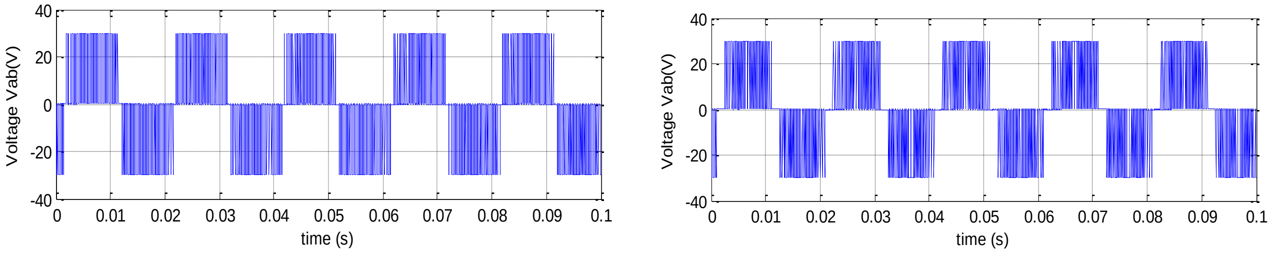
To validate the modified SVM technique and see the effectiveness of this technique, a numerical simulation by MATLAB/Simulink was performed in this part.

A DC voltage of 30 V is firstly used in the simulation tests to allow afterward (in the discussion section) a comparison of the results with those of the practical. The obtained simulation results are shown in Figs. 9-15. The control signals (S_a, S_b, and S_c) of the two-level inverter are shown in Fig. 9. These signals are pulses with voltage greater than 50 Hz. Fig. 10 shows simulation output voltage Va of both techniques and the maximum value of V_a is 20 V. The frequency of this signal is 50 Hz, which is the same as the network frequency. The simulation results of the line output voltage V_{ab} generated by the two-level inverter supplied with a DC voltage of 30 V are presented in Fig. 11. It can be noted the maximum value of V_{ab} is 30 V. From Fig. 11, we see that the frequency of the V_{ab} signal is 50 Hz. This is because the inverter does not affect the frequency, but rather the maximum value of the signal. Fig. 12 indicates the output current (I_a) waveform, which is similar to the V_a waveform due to the resistive load (R) used. The maximum magnitude of output current is 0.2 A. Knowing that the frequency of the current signal is the same as the frequency of V_a and V_{ab}. Through Figs. 13-15, we note that the harmonics of voltage and current for the modified SVM technique are considerably reduced compared to the traditional PWM technique. Table 4 shows the THD values obtained for both strategies during simulation testing. The almost same THD values are obtained for different values of the DC voltage in the range 20-35 V. Through the simulation results, we find that the proposed SVM method reduced THD value by about 12%, 10%, and 11% for current (I_a), simple voltage (V_a) and compound voltage (V_{ab}) compared to method traditional PWM. From observing these ratios, we find that they are very acceptable. Moreover, the simplicity of the algorithm is among the main goals of the proposed SVM method.



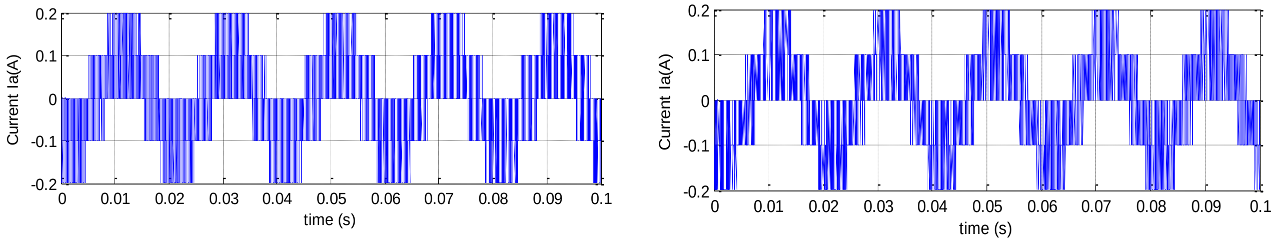
(a) (b)

Fig. 10 Phase output voltage (V_a); a) PWM and b) modified SVM.



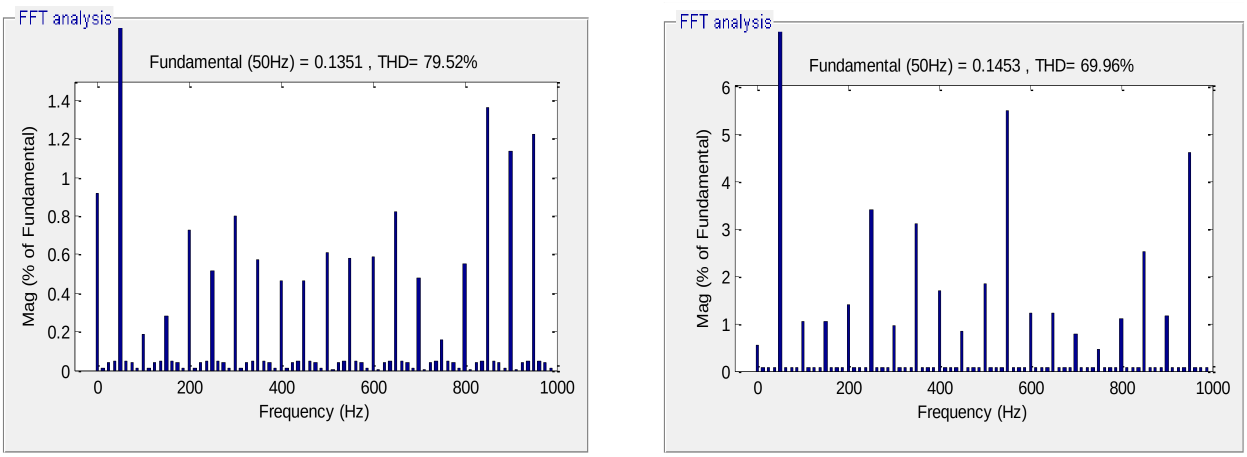
(a) (b)

Fig. 11 Line output voltage (V_{ab}); a) PWM and b) modified SVM.



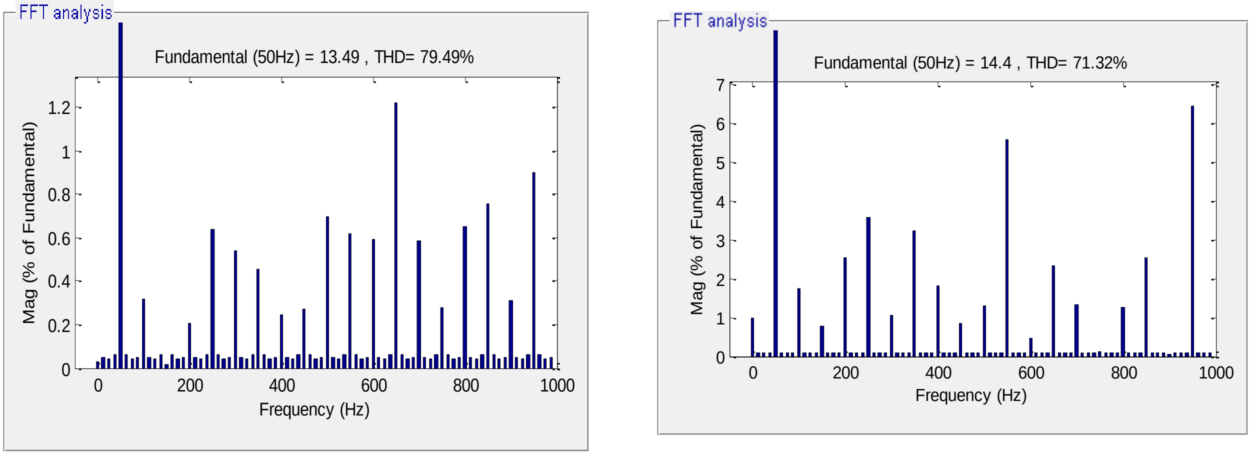
(a) (b)

Fig. 12 Line output current (I_a); a) PWM and b) modified SVM.



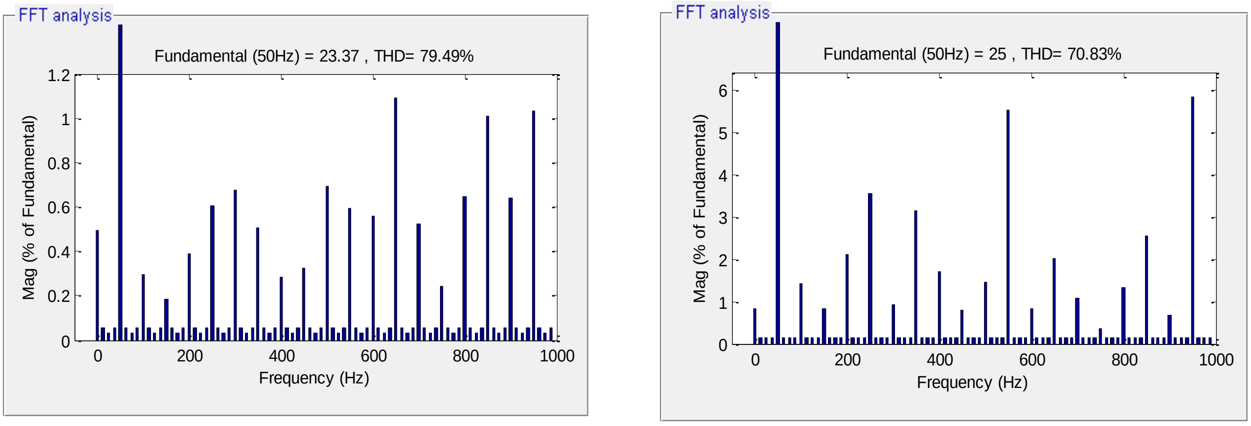
(a) (b)

Fig. 13 THD value of current I_a; a) PWM and b) modified SVM.



(a) (b)

Fig. 14 THD value of voltage V_a; a) PWM and b) modified SVM.



(a) (b)

Fig. 15 THD value of voltage V_{ab}; a) PWM and b) modified SVM.

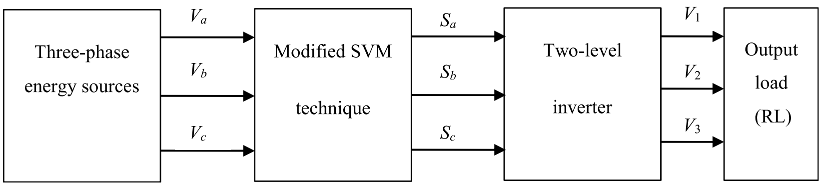


Fig. 16 Block diagram of the two-level inverter (output load is RL).

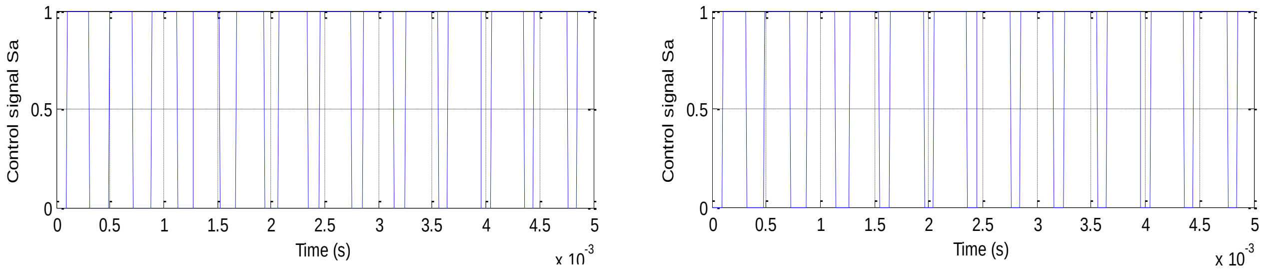
Table 5 Simulation values of THD for resistive load.

Techniques	THD value [%]		
	V_a	V_{ab}	I_a
PWM	123.85	123.84	3.11
Modified SVM	111.25	111.04	2.94

5.2 Second Part: Load RL

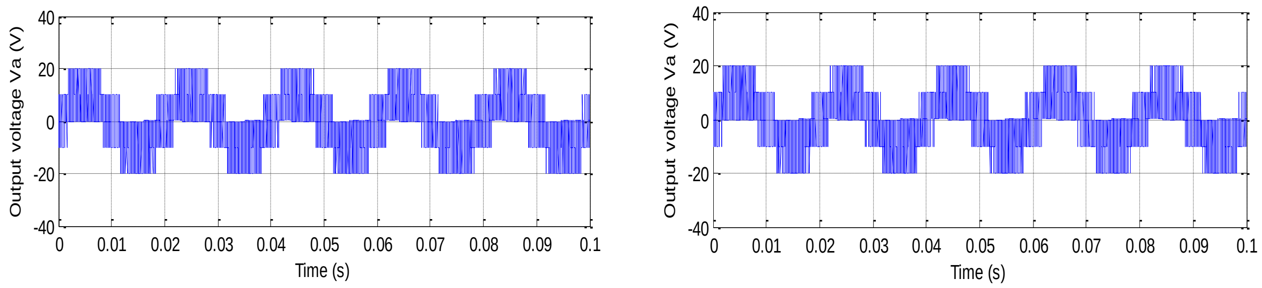
In this part, we will replace the load R with the load RL, where the values of R and L are 1 Ω and 26 mH, respectively. The simulation block diagram of the proposed technique is given in Fig. 16. The control signal (S_a) of the inverter for the two methods is shown in Fig. 17. This signal has a frequency greater than the frequency of the network and its form is of consecutive pulses. The results of digital simulations of this case are shown in Figs. 18 to 23. Fig. 18 represents the voltage output V_a of the inverter. By observing this figure, we find that the inverter gives 4 levels of voltage V_a, and the largest value for voltage is 20 V, while the minimum value is -20 V. The frequency of the voltage (V_a) signal, is 50 Hz, which is the same as the network frequency. The voltage V_{ab} of the inverter is represented in Fig. 19. The largest value for this voltage is 30 V and the smallest value is –30 V. The frequency of this signal is 50 Hz, which is the same as the frequency of the V_a signal. This is because the inverter affects the maximum value and not the frequency of the signal. The output current of the inverter is shown in Fig. 20. We note that the electric current is sinusoidal, with a maximum value of about 1 A and a frequency of 50 Hz.

Figs. 21-23 represent the THD value of voltage and current for the modified SVM method and the PWM method. By analyzing these figures, we find that the proposed SVM method provided better results than the PWM method, reducing the value of THD in the case of the load RL for the inverter as well. The results obtained are listed in Table 5. Through this table, we find that the reduction ratio for the proposed method was as follows: current (6%), simple voltage (10%), and compound voltage (10%). It can be concluded from Tables 4 and 5 that the proposed SVM method is the best method to use in controlling the inverter and even the multi-level inverter, and this is because of the simplicity of the algorithm of this proposed SVM method.



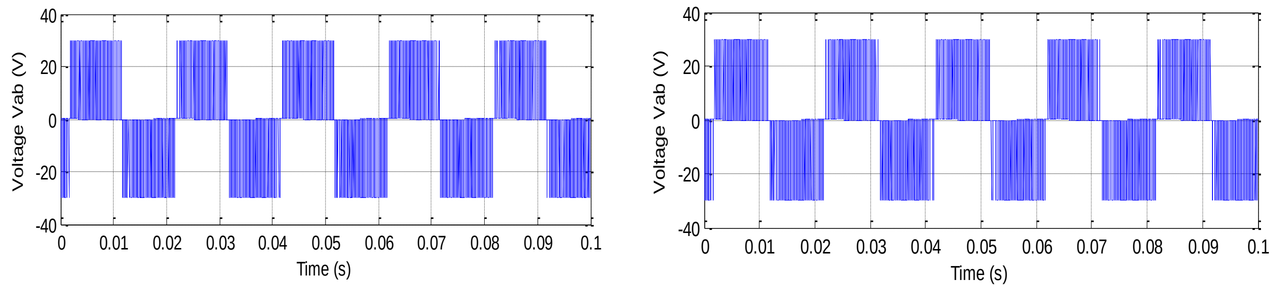
(a) (b)

Fig. 17 Control signals; a) PWM and b) modified SVM.



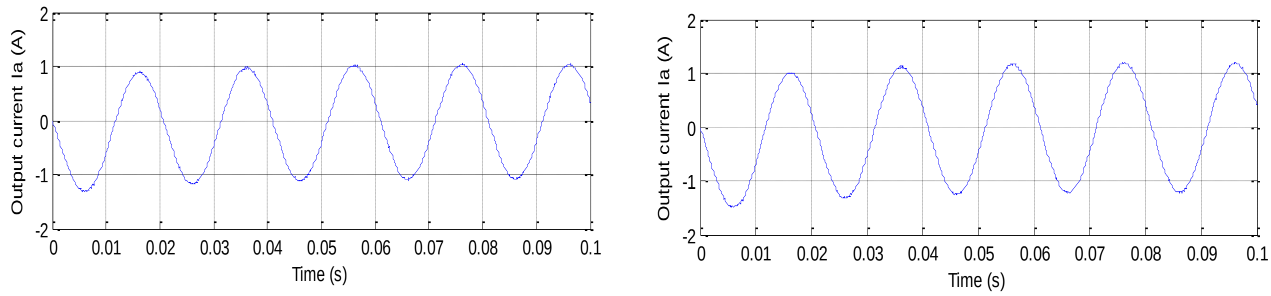
(a) (b)

Fig. 18 Phase output voltage (V_a); a) PWM and b) modified SVM.



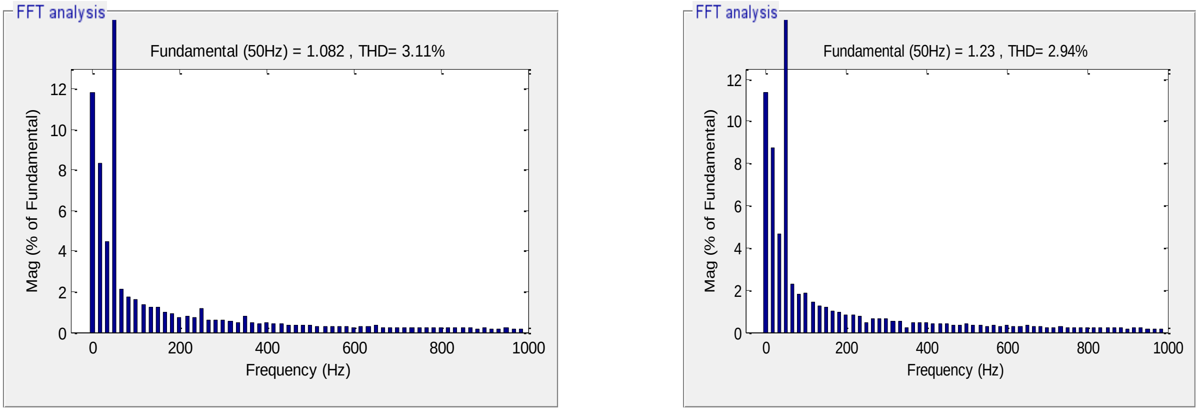
(a) (b)

Fig. 19 Line output voltage (V_{ab}); a) PWM and b) modified SVM.



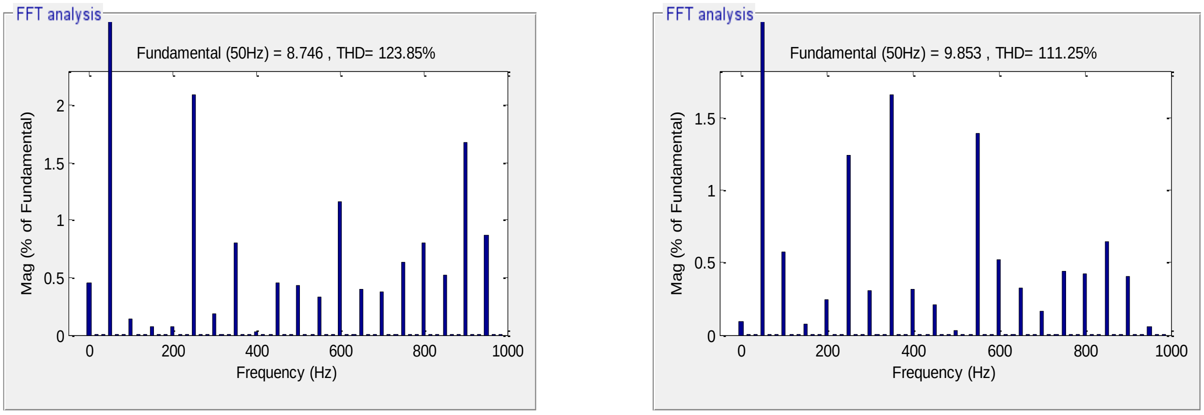
(a) (b)

Fig. 20 Phase output current (I_a); a) PWM and b) modified SVM.



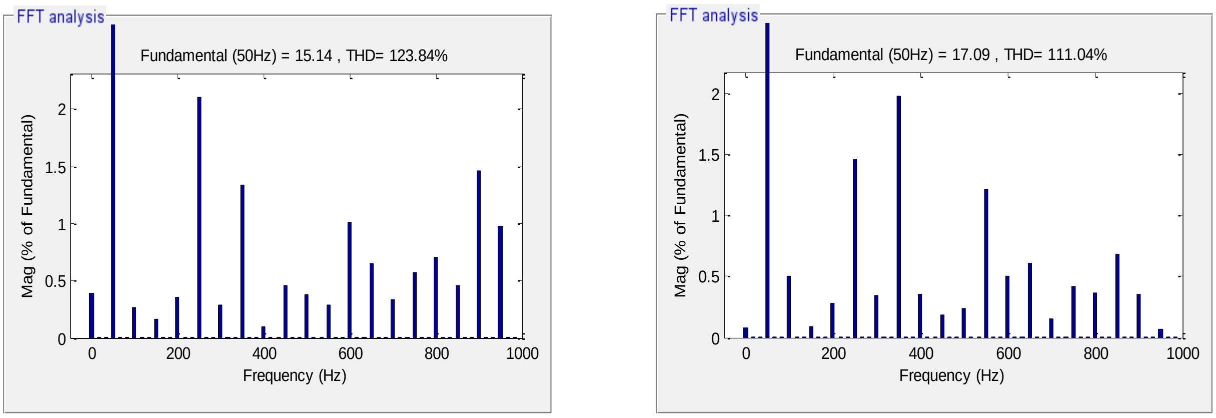
(a) (b)

Fig. 21 THD value of current (I_a); a) PWM and b) modified SVM.



(a) (b)

Fig. 22 THD value of voltage (V_a); a) PWM and b) modified SVM.



(a) (b)

Fig. 23 THD value of voltage (V_a); a) PWM and b) modified SVM.

6 Experimental Results

In this part, the scheme of the modified SVM technique is implemented to prove the validity of the proposed method. The photo of the implemented setup is shown in Fig. 24. The values of DC voltage sources and R load are the same as those used in the simulation test (30 V and 100 Ω, respectively) for a fair comparison of the results obtained. The obtained results are evaluated to verify the performance of the modified SVM technique for a two-level inverter.

The experimental waveform of the output voltage (V_a) for the traditional inverter controlled by the modified SVM method is shown in Fig. 25. As shown in this figure, the two-level inverter can produce 4 levels and the maximum value of output voltage is 20 V, and the frequency of this signal is 50 Hz. Fig. 26 shows the experimental output voltage (V_{ab}) of the two-level inverter and note that the maximum value of V_{ab} is 30V and its frequency is 50 Hz. Fig. 27 shows the experimental FFT of the output voltage (V_a). It is seen that the 3^{rd}, 5^{th}, and 7^{th} harmonics are efficiently mitigated. The same remark is for Fig. 28 which shows the experimental FFT of the line output voltage (V_{ab}). From these figures, it is clear that the low-order harmonics are almost eliminated compared to the PWM technique. The results obtained from the experiment prove the performance of the modified SVM technique for the traditional inverter.

7 Discussion

The experimental results presented in Section 5 correctly validated the modified SVM strategy designed to control the traditional inverter simply and efficiently.

Although experimental was performed on a prototype low power inverter, the modified SVM strategy can be applied similarly for a high power inverter, because the operating principle, theory, and modeling behind the modified SVM strategy remain the same, regardless of the level of inverter power.

From these results, it is clear that the low-order harmonics are almost eliminated compared to the traditional PWM technique. The results show that the proposed modified SVM technique has a good behavior suitable for inverter applications. This is what was shown by the experimental and simulated results at the same time. It was confirmed that the designed modified SVM strategy application is feasible for low-energy applications, capturing the main advantages of this kind of modulation: simple implementation and fast response.

The percentages mentioned above for the THD have been estimated by the reduction ratio (RR) of the THD value (RR_{THD}) given by (8):

$$RR_{THD}\,[\%] = \frac{THD_{s1} - THD_{s2}}{THD_{s1}} \tag{8}$$

where, THD_{S1} and THD_{S2} represent the THD values of the current, phase voltage, and line voltage obtained for the PWM method and proposed SVM.

Table 6 shows the THD values obtained for both strategies during simulation testing. It can be concluded from Table 6 that the proposed SVM method gives better results in controlling the inverter and even the multi-level inverter.

Fig. 24 Equipment used for experimental tests.

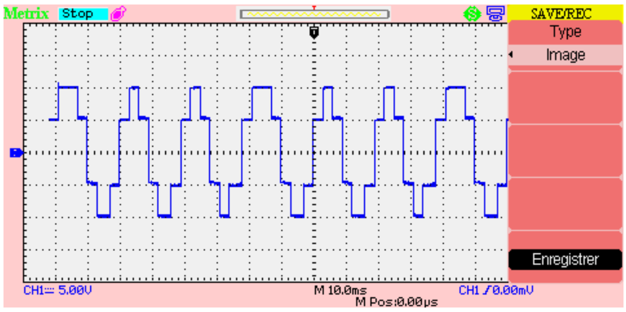


Fig. 25 The experimental measurement of V_a (modified SVM).

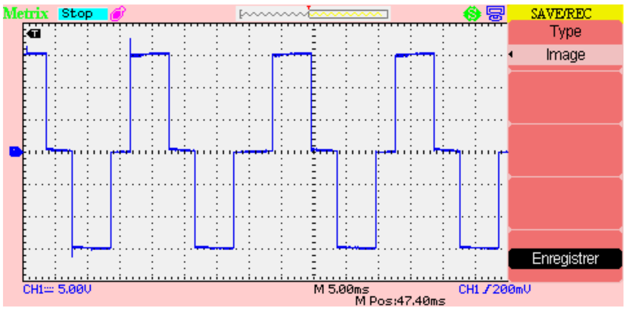


Fig. 26 The experimental measurement of V_{ab} (modified SVM).

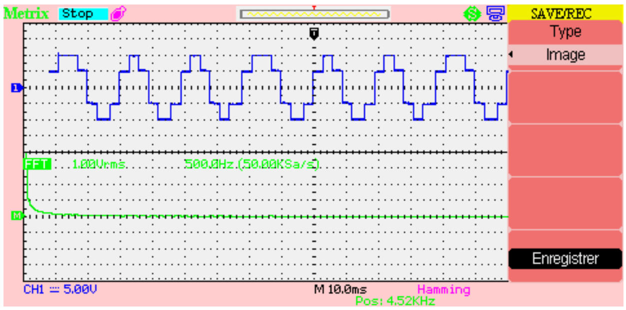


Fig. 27 Output voltage (V_a) and its spectrum in the case of the experiment (modified SVM).

Table 6 Simulation values of THD for resistive load.

Strategy	THD value (%)					
	Load R			Load RL		
	V_a	V_{ab}	I_a	V_a	V_{ab}	I_a
PWM	79.49	79.49	79.52	123.85	123.84	3.11
Proposed SVM	71.32	70.83	69.96	111.25	111.04	2.94
RR_{THD} [%]	10.28	10.89	12.02	10.17	10.34	5.47

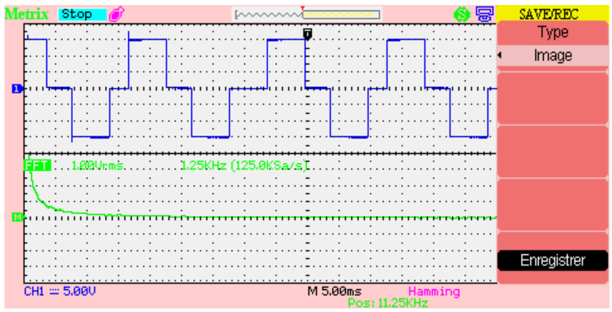
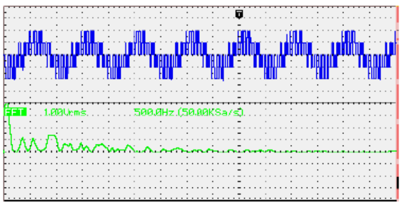
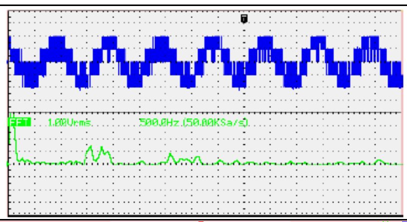
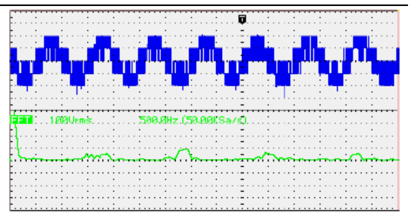
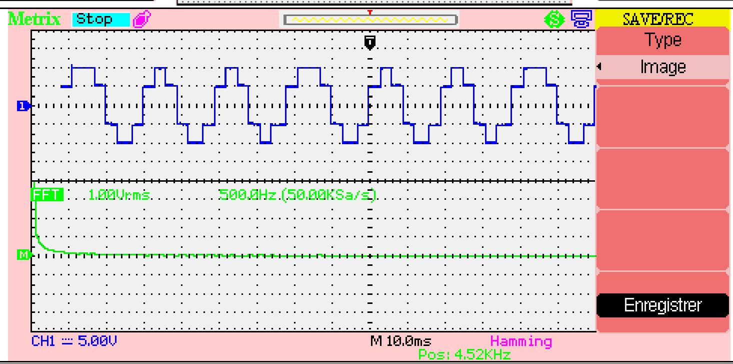


Fig. 28 Output voltage (V_{ab}) and its spectrum in the case of the experiment (modified SVM).

Table 7 Comparative results between proposed SVM technique and other techniques.

Criteria	Ref [46]			Ref [47]		Ref [44]			Proposed SVM
	PWM	Traditional SVM	Neural SVM	SPWM	SVPWM	SPWM	SVPWM	SVM with offset signal	
Simplicity	Simple	Complicated	Simple	Simple	Complicated	Simple	Complicated	Simple	Simple
Robustness	Low	Medium	High	Low	High	Low	High	Medium	High
Implementation	Easy	Difficult	Easy	Easy	Difficult	Easy	Difficult	Easy	Easy
Completion cost	Low	High	Medium	Low	High	Low	High	Medium	Low
THD [%]	High	High	Medium	High	Medium	High	Medium	Medium	Medium

Table 8 Comparison of experimental results between Ref. [47] and the proposed modified SVM technique.

	PWM	SVM	Neural SVM
Ref. [45]			
Proposed SVM technique			

It can be concluded from Table 6 that the proposed SVM method gives better results in controlling the inverter and even the multi-level inverter. On the other hand, the experimental results showed how efficient the proposed method is compared to the traditional method for a low power inverter. Because the proposed method ensures a low value of THD, filters can be made at lower costs.

Table 7 represents a comparative study between the proposed SVM strategy and several methods published in several scientific works.

In Table 8, we compare the experimental results obtained in this paper with Ref. [47]. The comparison between the two works in terms of a value of harmonic distortion and also in terms of eliminating unwanted frequencies for simple voltage (V_a), especially high frequencies. By noting Table 8, we find that the proposed modified SVM method is very effective in removing unwanted frequencies as well as reducing the value of harmonic distortion compared to PWM, traditional SVM, and neural SVM.

8 Conclusion

In this work, a brief review of the SVM methods has been performed first. Then, a new algorithm for the SVM method of the two-level inverter was introduced. The proposed SVM technique was compared with the traditional PWM method and other reference methods from the literature. The results of the comparison shown in Tables 7 and 8 highlight the following advantages of the proposed modulation scheme:

- Requires a lower implementation effort and reduces the voltage and current harmonics by about 9% compared to the traditional PWM method.
- The modified SVM is easy to implement compared to the traditional SVM strategy.
- Calculation of the minimum and maximum value of three-phase in the structure of a modified modulation scheme is a simpler method than other modulation techniques.
- A simple algorithm of the SVM technique was proposed and confirmed by experimental and numerical simulation.

Also, to verify the effectiveness of the modified SVM technique, the experimental results using dSPACE are presented.

In summary, the main findings obtained are the following:

- The experimental results confirmed the validity of the simulated results.
- The modified SVM technique reduces the voltage ripples for both R and RL loads by about 10% compared to the traditional PWM method; the THD for current decreases by approximately 12% and 5.5% for R load and RL load, respectively.
- The modified SVM technique is easier to implement and a simpler algorithm compared to traditional SVM.
- The modified SVM technique based on the Min-Max values improves the THD value of the two-level inverter.
- Effectual modified SVM strategy is a better modulation strategy for traditional three-phase inverter when compared to other methods reported in this work.

This proposed new method is tested in this paper on a small energy source and uses a resistive and resistive-inductive load to confirm that this proposed modified SVM method reduces the value of THD as well as voltage ripples. In future research, this proposed modified SVM control method will be implemented on a multi-level inverter of a higher power, highlighting its performance without an increase in its costs or weight.

In other words, the next experimental work will be about improving the performance and effectiveness of the modified SVM technique.

Intellectual Property

The authors confirm that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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CRediT Authorship Contribution Statement

H. Benbouhenni: Idea & conceptualization, Software and simulation, Original draft preparation, Methodology, Analysis, Revise & editing, Research & investigation. **N. Bizon:** Project administration, Verification, Supervision, Revise & editing, Funding acquisition, Analysis. **I. Colak:** Research & investigation, Data curation, Methodology, Verification, Original draft preparation.

Declaration of Competing Interest

The authors hereby confirm that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to "Iranian Journal of Electrical and Electronic Engineering".

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H. Benbouhenni was born in Chlef, Algeria. He is a Ph.D. in the Department of Electrical Engineering at the ENPO-MA, Oran, Algeria. He received a M.A. degree in Automatic and Informatique Industrial in 2017. He is currently Professor with the University of Nisantasi, Turkey. He is editor of seven books and more than 130 papers in scientific fields related to Electrical Engineering. His research activities include the application of robust control in wind turbine power systems.

N. Bizon was born in Albesti de Muscel, Arges county, Romania, 1961. He received the B.Sc. degree in Electronic Engineering from the Polytechnic University of Bucharest, Romania, in 1986, and the Ph.D. degree in Automatic Systems and Control from the same university, in 1996. From 1996 to 1989, he was in hardware design with the Dacia Renault SA, Romania. He is currently a Professor at the University of Pitesti, Romania. He received two awards from Romanian Academy, in 2013 and 2016. He is editor of ten books and more than 500 papers in scientific fields related to Energy. His current research interests include power electronic converters, fuel cell and electric vehicles, renewable energy, energy storage system, microgrids, and control and optimization of these systems.

I. Colak was born in 1962 in Turkey. He received his diploma in Electrical Engineering from Gazi University, Turkey in 1985. Then he did his M.Sc. in Electrical Engineering in the field of Speed Control of Wound Rotor Induction Machines Using Semiconductor Devices at Gazi University in 1991. After that, he did his M.Phil. at Birmingham University in England by preparing a thesis on high-frequency resonant DC link inverters in 1991. Finally, he did his Ph.D. at Aston University in England on mixed frequency testing of induction machines using inverters in 1994. He became an Assistant Professor, an Associate Professor, and a Full Professor in 1995, 1999, and 2005, respectively. He has published more than 108journal papers, 239 conference papers, and 7 books in different subjects including electrical machines, drive systems, machine learning, reactive power compensation, inverter, converter, artificial neural networks, distance learning automation and alternating energy sources. More than 212 of his papers have been cited in SCI. His papers have received more than 2199 citations by 2128 papers. His Thomson Reuters h-index is 24 and average citation per paper is 10.37. In Scopus, h-index is 30. His 278 papers have received 3560 citations from 2040documents. He supervised 23 M.Sc. students and 14 Ph.D. students. He is a senior member of IEEE, member of IES, IAS, PELS, and PES. Last twenty years, he has been concentrated his studies on renewable energy and smart grids by publishing papers, journals (www.ijrer.org) (www.ijsmartgrid.org) and organizing international IEEE sponsored conferences (www.icrera.org), (icsmartgrid.org). He also spent around 3 years at European Commission Research Centre (JRC) in the Netherlands. He served as the head of department, dean and vice rector at Gazi University, Istanbul Gelisim University and Nisantasi University. He is currently a full professor at Nisantasi University. Professor Colak achieved a great success of 10% by being included in the "World's Most Influential Scientists" 2% list, which was created USA Stanford University considering the "Works of the Year 2020".