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A Comparative Study between Sine-Triangular Modulation and Six-Step Modulation Techniques for Three Phase Inverters

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ABSTRACT
six pulse inverters are commonly used in renewable Energy applications to convert the DC voltage to a three-phase AC voltage with a constant frequency and constant rms value. It is typically desired to obtain an AC voltage waveform with high fundamental component amplitude of voltage waveform and low harmonic contents. To achieve that, various modulation techniques are used. In this paper, a comparison between sine-triangular modulation and six-step modulation is presented. To set the stage, analytical equations are defined for a three-phase inverter supplying an inductive load. Using MatLab/Simulink tool, the voltage and current waveforms are obtained and the total harmonic distortion (THD) is evaluated for the two modulation techniques. It is concluded from the results that the sine-triangular modulation technique leads to lower THD while the six-step modulation technique gives higher fundamental component amplitude of the voltage waveform.
Keywords - Low order harmonics, sine-triangular modulation, six pulse inverters, six-step modulation, three phase inverters, total harmonic distortion.

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I. INTRODUCTION

Renewable energy resources have been of interest for the past few decades. Although these energy sources are sustainable and friendly to the environment, the continuous variation of these resources make connecting them to the utility grid, which require constant voltage and frequency, a very challenging task. To tackle this issue, the energy harvested from renewable energy resources is stored in batteries in form of DC. As a result, a three-phase inverter is a very crucial component in the renewable energy system. The function of the three phase inverter is to convert the DC voltage stored in the battery to an AC voltage with the same voltage magnitude and frequency as the utility grid [1]-[6].

The performance of the three-phase inverter and the magnitude of the harmonic contents in the voltage waveform is greatly affected by the switching technique [7]-[12]. For instance, six-step modulation technique is relatively easy to implement and yields a large output voltage range; however, the output voltage waveform contains a significant low order harmonic contents which require special filtering techniques [7], [8]. On the other hand, sine-triangle modulation technique is more complicated to implement and has lower output voltage range; however, the low order harmonic contents in the voltage waveform is eliminated [8], [9].

In this paper, a comparison between six-step modulation technique and sine-triangle modulation technique is considered. The performance of a three-phase inverter supplying an inductive load is evaluated for each case when the switching pulses are generated using the two different modulation techniques.

This paper is organized as follow. In Section II, the three-phase bridge converter is analyzed. In Section III, the six-step modulation technique is discussed. The sine-triangle modulation technique is considered in Section IV. In Section V, the simulation of the three-phase inverter supplying an inductive load is implemented using MatLab/Simulink software and a comparison between the two modulation techniques is presented. Finally, Section VI concludes the work of this paper.

II. THREE-PHASE BRIDGE CONVERTER

The connection of the three phase inverter is depicted in Fig. 1. This type of inverters is composed of six controllable switches T1 – T6 and six diodes D1 – D6. The main function of the diodes is to provide a path for the inductive current when the switch is turned off.

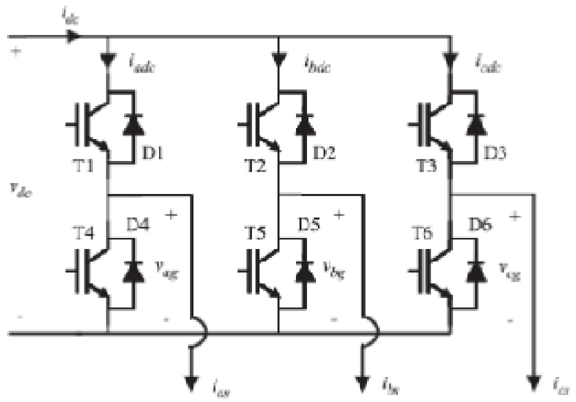

Fig. 1: Three-phase bridge converter connection

As shown, v_{dc} denotes the input dc voltage, v_{ag}, v_{bg} and v_{cg} denote the line-to-ground voltages for each phase and i_{as}, i_{bs} and i_{cs} denote the load currents for each phase.

The line-to-line voltages may be expressed in terms of the line-to-ground voltages as

$$v_{abc} = v_{ag} - v_{bg} \quad (1)$$

$$v_{bcs} = v_{bg} - v_{cg} \quad (2)$$

$$v_{cas} = v_{cg} - v_{ag} \quad (3)$$

It can be shown from Fig.1that the total dc current equals the sum of the dc currents in all three legs; thus,

$$i_{dc} = i_{adc} + i_{bdc} + i_{cdc} \quad (4)$$

Typically, it is desired to obtain the line-to-neutral voltages which are related to the line-to-ground and the neutral-to-ground voltages as:

$$v_{as} = v_{ag} - v_{ng} \quad (5)$$

$$v_{bs} = v_{bg} - v_{ng} \quad (6)$$

$$v_{cs} = v_{cg} - v_{ng} \quad (7)$$

By adding equations (5)-(7) and rearranging one may obtain

$$v_{ng} = \frac{1}{3}\left(v_{ag} + v_{bg} + v_{cg}\right) - \frac{1}{3}\left(v_{as} + v_{bs} + v_{cs}\right) \quad (8)$$

For a balanced three-phase system, the sum of the line-to-neutral voltages equals zero and thus,

$$v_{ng} = \frac{1}{3}\left(v_{ag} + v_{bg} + v_{cg}\right) \quad (9)$$

By substituting (9) into (5)-(7), one can yield

$$v_{as} = \frac{2}{3}v_{ag} - \frac{1}{3}v_{bg} - \frac{1}{3}v_{cg} \quad (10)$$

$$v_{bs} = \frac{2}{3}v_{bg} - \frac{1}{3}v_{ag} - \frac{1}{3}v_{cg} \quad (11)$$

$$v_{cs} = \frac{2}{3}v_{cg} - \frac{1}{3}v_{ag} - \frac{1}{3}v_{bg} \quad (12)$$

III. SIX-STEP MODULATION

In the previous section, expressions for the inverter's output line-to-neutral voltages are obtained. In this section, the six-step modulation technique is discussed. In this modulation technique, the switching pulses T1 – T6 are generated using the logic circuit shown in Fig.2

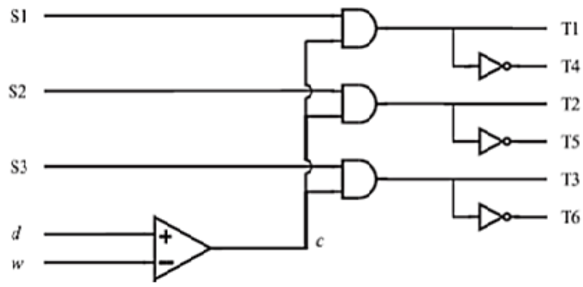

Fig. 2: Switching pulse generating circuit for six-step modulation

The signals S1 – S3 as function of the inverter angle, θ_c,are illustrated in Fig.3

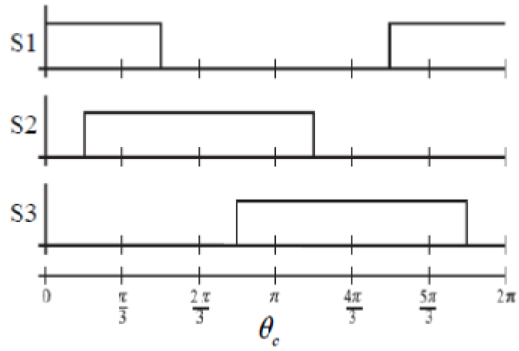

Fig. 3: Signals S1 – S3 as functions of θ_c

To ensure a controllable output voltage, the duty cycle, d is defined as shown in Fig.2. This is achieved by comparing the duty cycle with the signal w as depicted in Fig. 4.

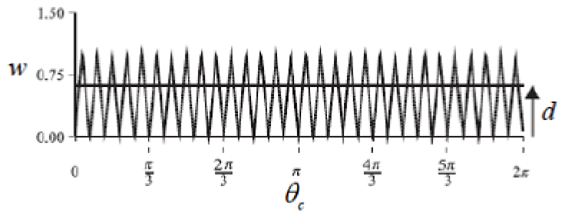

Fig. 4: The duty cycle and signal w as functions of θ_c

IV. SINE-TRIANGLE MODULATION

Now the sine-triangle modulation is considered in this section. As shown in Fig.5, the switching pulses are generated by comparing triangular wave w with sinusoidal duty cycles d_a, d_b and d_c, where,

$$d_a = d\cos\theta_c \qquad (15)$$

$$d_b = d\cos\left(\theta_c - \frac{2\pi}{3}\right) \qquad (16)$$

$$d_c = d\cos\left(\theta_c + \frac{2\pi}{3}\right) \qquad (17)$$

Where d is the amplitude of the duty cycles

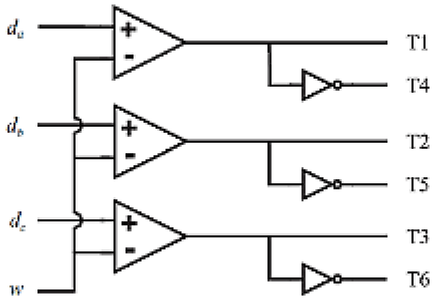

Fig. 5: Switching pulse circuit for sine-triangle modulation

It should be mentioned that the frequency of the duty cycles equals the fundamental frequency while the frequency of the triangle wave corresponds to the switching frequency which is relatively very high. Therefore, the duty cycle waveforms seem to be constant when compared to the triangle wave as depicted in Fig.6.

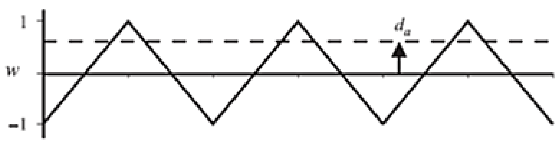

Fig. 6: Sine-wave and triangle wave comparison

V. SIMULATION AND RESULTS

In this section, the mathematical model of the six pulse inverter which is supplying an inductive load is implemented using Simulink environment as depicted in Fig.7. The switching pulses which operate the inverter switches are first generated using six-step modulation and then using sine-triangle modulation. The performance of the inverter which corresponds to each modulation technique is presented in this section.

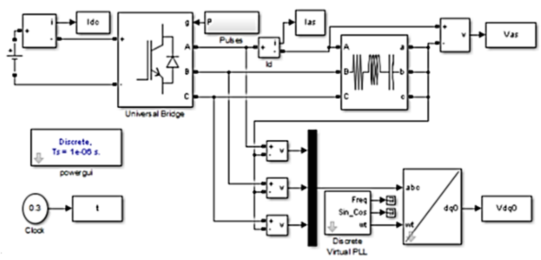

Fig. 7: Simulink model of the inverter supplying RL load

For both cases, the obtained results are based on the parameters depicted in Table I.

TABLE I

Table Head	MODEL PARAMETERS		
	Parameter	***Symbol***	***Value***
	DC voltage	V_{dc}	100 V
	Load resistance	R_L	2 Ω
	Load Inductance	L_L	1 mH
	Fundamental frequency	f	100 Hz
	Switching frequency	f_s	3 kHz
	Duty cycle	d	0.6

A. Using Six-Step Modulation

First, the six-step modulation technique is used to generate the inverter switching pulses. As shown in Fig. 8, the ac voltage waveform is composed of three levels which should be expected from equations (10) – (12). As shown, the voltage waveform is not pure sinusoid and thus it contains harmonic contents.

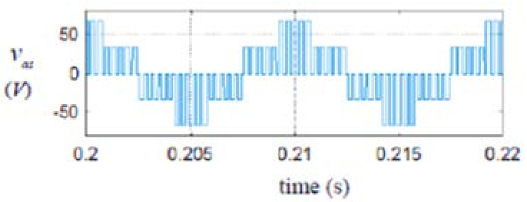

Fig. 8: Load voltage versus time for six-step modulation

Fig. 9 shows the magnitude of each harmonic normalized to the magnitude of the fundamental signal. Thus, the normalized magnitude of the fundamental signal equals one and the normalized magnitude of each harmonic signal represent the ratio between each harmonic magnitude and the fundamental magnitude. Although some high order harmonics seem to have a relatively large magnitude, they can be easily filtered using a simple low pass filter. However, filtering the low order harmonics is more challenging task [11], [12].

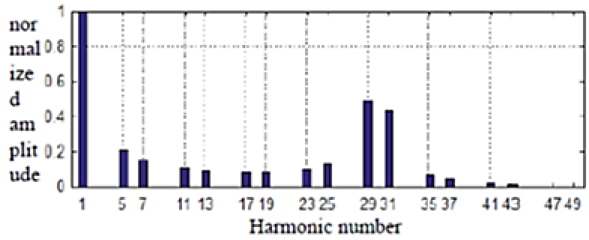

Fig. 9: Frequency spectrum for six-step modulation

The voltage reference angle is selected such that the direct axis voltage, V_d equals zero and the quadratic axis voltage, V_q equals the magnitude of the fundamental voltage waveform. As depicted in Fig 10, the average of V_d is zero and the average of V_q equals the magnitude of the fundamental component of the voltage waveform. However, they both have large harmonic contents.

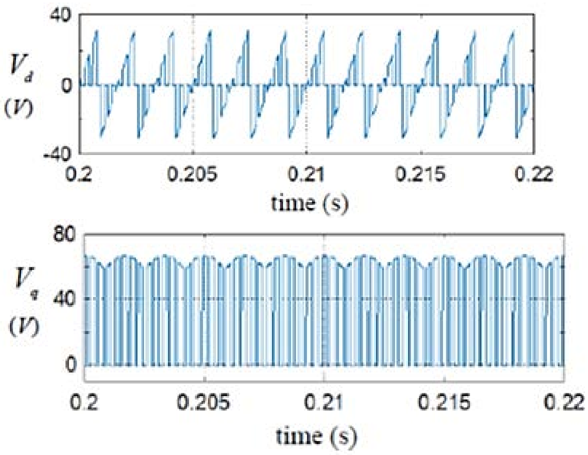

Fig. 10: V_d and V_q versus time for six-step modulation

When a RL load is connected between the output terminals of the inverter, most of the high order harmonic contents in the current waveform are filtered by the load inductance as depicted in Fig.11. However, the low order harmonics are still evident in the current waveform and they require a specially designed filter to eliminate them without distorting the fundamental waveform. As a result, the total harmonic distortion (THD) is 16.34%, which is higher than the maximum percentage recommended by IEEE, i.e. 5%

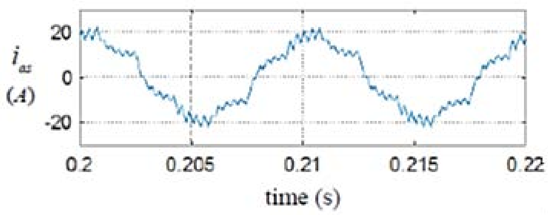

Fig. 11: Load current versus time for six-step modulation

Due to the effect of switching, the DC current will also contain harmonic contents as illustrated in Fig. 12.

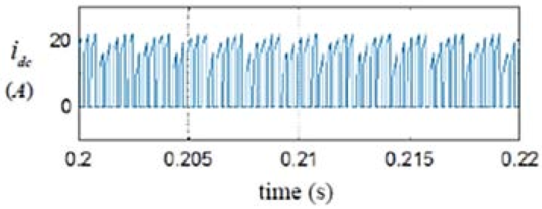

Fig. 12: DC current versus time for six-step modulation

B. Using Sine-Triangle Modulation

Now the six pulses of the inverter are obtained using the sine-triangle modulation technique. The line to neutral voltage waveform is depicted in Fig.13.

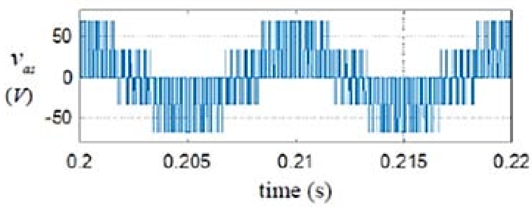

Fig. 13: Load voltage versus time for sine-triangle modulation

In this modulation technique, the low order harmonic is eliminated as shown in the harmonic spectrum shown in Fig.14. It is evident that using sinusoidal duty cycles is the reason behind the elimination of the low order harmonic.

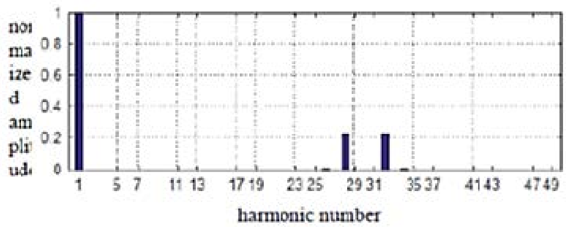

Fig. 14: Frequency spectrum for sine-triangle modulation

The direct axis and quadratic axis voltage waveforms are depicted in Fig. 15.

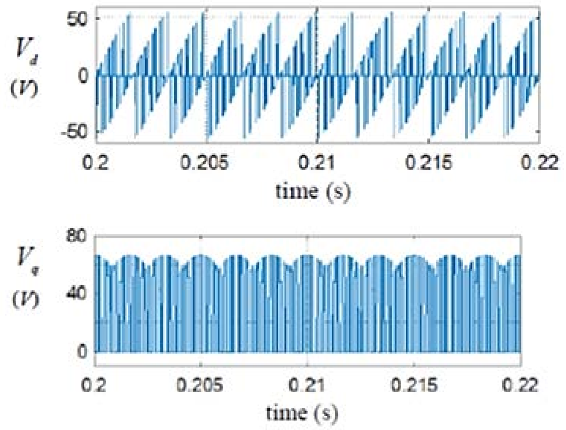

Fig. 15: V_d and V_q versus time for sine-triangle modulation

Since the voltage waveform contains only high order harmonics, most of the harmonic contents in the current waveform are easily filtered out by the load inductance as shown in Fig. 16. It is very clear that the current waveform shown in Fig. 16 is closer to pure sinusoid compared to the current waveform depicted in Fig. 11.therefore; the THD in the case of sine-triangle modulation is as low as 3.44% which satisfy the IEEE standard.

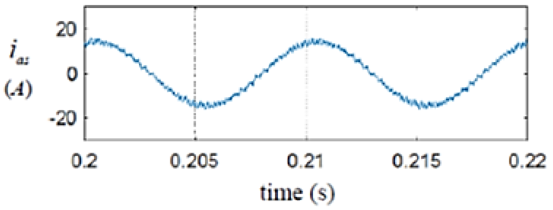

Fig. 16: Load current versus time for sine-triangle modulation

The DC current also contains high order harmonics as illustrated in Fig. 17. However, the average value of the DC current is less than the value when the six-step modulation is used. This is caused by the fact that, the RL load absorbs less power in the sine-triangle modulation due to the reduction in the magnitude of the fundamental component of the output voltage.

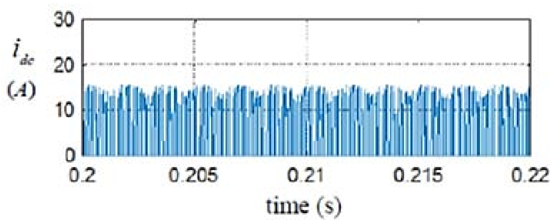

Fig. 17: DC current versus time for sine-triangle modulation

VI. CONCLUSION.

In this paper, a comparative study between six-step and sine-triangle switching techniques of a three-phase inverter supplying an RL load were considered. First, the three-phase inverter and the load were simulated using Simulink tool. After defining the model parameters, the inverter performance was evaluated for the two modulation techniques. It was noticed from the simulation results that using six-step modulation had led to a higher fundamental voltage magnitude while it had significant low order harmonics. On the other hand, the sine-triangle modulation had led to a lower fundamental voltage magnitude while the low order harmonic contents were eliminated. This makes the six-step modulation technique suitable for robust loads which require large voltage range while sine-triangle modulation technique is suitable for loads that require a voltage supply with a good quality.

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