An optimum PWM technique to maximize the continuity of inverter output

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Abstract

New varied-pulse-width technique (VPW) for a high performance power inverter has been presented in this paper. The VPW technique improves the inverter output voltage in the way to produce an output cycle of a less discontinuity and fewer harmonic contents. In VPW technique, the original pulse-width of an inverter operation is divided into multiple pulses of variable widths per half cycle. The division of an original single-pulse of width (δ) into number of pulses (p) per half cycle produces uniform pulses of width (σ). Increasing the pulse-width for some pulses and decreasing the same amount of width from other pulses, result in variable-width pulses. To maintain the same operation for the inverter, the adding and subtracting of pulse-widths for the pulses must be equivalent. Due to the software ability of modifying the number of pulses per half cycle and their widths, the VPW technique provides an inverter operation with less generation of harmonics. Test results are presented to examine the performance of VPW technique and to compare it with the performance of the conventional methods.

Key Words: PWM inverter, Energy conversion, Power converters, PWM control, power processor.

Symbols

PWM	Pulse-Width Modulation
p	number of pulses per half cycle
A_c	carrier signal amplitude
A_r	reference signal amplitude
δ	original single-pulse per half cycle
σ	uniform pulse width
α	gating angle
v_0	inverter output voltage
Vs	dc- source voltage of the inverter
n	harmonic order
m	modulation index
k	pulse order
σ_k	pulse-width of k^{th} pulse order
MLP	most-left pulse
T_s	half cycle period

1. Introduction

Power electronic systems are used in industry to process and control the flow of electric energy by supplying the voltages and currents in a form that are optimally suited for the loads and providing energy conservation. The inverter is a dc-ac converter that its output voltage can be controlled by varying the conduction time of the power semiconductor switches [1]. The employing of inverters eliminates the throttling and restrictive devices and offer the possibility for significant energy saving [2, 3]. The output of an ideal inverter is a sinusoidal waveform but this is invalid for the practical inverter in which its output is discontinuous and contains harmonics. This discontinuous operation is undesirable for practical applications due to its problems such as extra power losses [4, 5]. The Pulse-Width- Modulation (PWM) inverters convert the constant voltage into a controlled magnitude and frequency output voltage. A discontinuity and harmonic effect appear in the inverter output voltage due to PWM- discontinuity technique [6, 7]. Many schemes for the pulse-width- modulated inverters tried to make the inverter output voltage close to a sinusoidal form as possible. As the inverter output voltage is close to a sine wave as a better output voltage can be obtained with fewer harmonics [8, 9]. In a sinusoidal pulse-width-modulation control, a sinusoidal reference signal is produced and it compares with a triangular carrier signal to generate several pulses per half cycle, in which the width of each pulse is varied depending on its corresponding amplitude of the sinusoidal reference signal [10, 11]. The inverter output voltage along with this technique has little harmonic amplitudes. If the reference signal is taken as a rectangular form, a number of pulses of a uniform width are produced. This type of technique is known as multiple-pulse width modulation (MPWM) [12]. Discontinues operation of this technique produced counted harmonics in the inverter output voltage.

Many other techniques were developed to increase the fundamental component of the inverter output voltage and improve its harmonic characteristics. In the stepped modulation technique the reference signal is stepped so that to generate an inverter output voltage close to the sinusoidal form [13]. The staircase modulation technique has modified the reference signal to a staircase form trying to obtain a high fundamental component of the inverter output voltage with improved harmonic performance [14]. Another form of modulation technique called trapezoidal modulation was developed to improve the inverter harmonic performance. In this technique the peak fundamental inverter output voltage is improved but the low order harmonics are counted [15].

In this work, the authors developed a software-model for new pulse-width technique to divide the original pulse of an inverter operation into multiple and variable-width pulses per half cycle. The software-model determines the conduction angles for the variable-width pulses and applied directly to the transistor drive of the inverter. The proposed technique gives an improved inverter operation due to its ability for making the inverter output voltage closer to the sinusoidal form and then produces less generation of harmonics. The results show that the harmonics can be modified and significantly decreased compared to that of the conventional pulse-width techniques, due to software ability of changing the widths of the pulses.

The rest of the paper is organized as follow; section 2 describes the traditional pulse-width-modulation techniques that implement to control the inverter gain, this is followed by a description of the new techniques and their equations for variable pulse widths in section 3. In section 4, results for different control techniques are presented and a comparison for harmonic contents in the inverter output voltage is made. Finally, conclusion and summary of the work is provided in section 5.

2. Traditional PWM techniques

The purpose of producing a single pulse of a changeable width per half cycle is to control the output voltage of the inverter. This is leading to a discontinuity operation and the harmonics will appear in the inverter output voltage. The PWM techniques were suggested to increase the number of pulses per a half cycle at variable pulse-widths for an improved inverter operation.

The single pulse-width modulation technique compares the triangular carrier signal with the rectangular reference signal to generate the positive and negative pulses required for inverter output voltage [7]. The reference signal determines the frequency of the inverter output voltage. The intersected points of reference signal and the carrier signal represent the gating angles (α), or the starting and ending instants of conduction angles (δ) for the transistors in the inverter drive.

In multiple-pulse width modulation technique (MPWM), instead of generating a single pulse per half cycle of inverter output voltage, multiple pulses of uniform widths in each half cycle were produced. This technique is reduced the amount of harmonics injected into output voltage compared to the single pulse-width modulation technique [12]. In this technique, two signals are generated to produce p-pulses per half cycle; the rectangular reference signal to determine the frequency of the inverter output voltage, and the triangular carrier signal to determine the number of pulses per single output cycle.

2.1 Sinusoidal PWM technique (SPWM)

The SPWM technique is the most common traditional one and it is used in practical inverters due to its low harmonic profile in the inverter output voltage. In sinusoidal pulse-width-modulation technique (SPWM), the width of each pulse is varied by generating a sinusoidal reference signal instead of a rectangular reference signal [10, 7]. This sinusoidal pulse-width-modulation technique gives a harmonic profile of lower distortion factor compared to that of multiple pulse-width-modulation and single pulse-width-modulation techniques.

The sinusoidal reference signal (v_r) at required frequency is compared with a triangular carrier signal (v_c) to produce the switching control signals. These signals control the on-state and off-state of the switching device. The triangular carrier signal is utilized to generate multiple pulses per output cycle, and varied pulse widths are obtained due to applying the sinusoidal reference signal. The amplitude ratio of the reference signal (A_r) to the carrier signal (A_c) controls the modulation index (m) and then the inverter output voltage. In the SPWM, there are variable pulse widths and the width of each pulse (σ_k) depends on its order (k). Therefore the effective value of the inverter output voltage is given in terms of (σ_k) and equals:

$$V_{eff} = V_s \left[\sum_{k=1}^{2p} \frac{\sigma_k}{\pi} \right]^{\frac{1}{2}} \tag{1}$$

3. New pulse-width technique

The design of multiple-pulse width modulation and sinusoidal-pulse width modulation control-modes need enormous hardware circuits to produce the reference signal and carrier signal that are required for generating the gating signals of the inverter-transistor drive. Also the complexity of the circuit makes the modification of the number of pulses per half cycle difficult. In practice, it is reasonable and intuitive to develop a control technique leading to minimum harmonic contents in the inverter output voltage towards to an optimum operation. In this work, a new software technique is developed to split the original pulse of an inverter operation into several pulses of varied- widths per half cycle. The pulse-splitting and pulse-width variation reduce the discontinuity in the inverter output voltage and then improve the inverter operation. Also the software-mode of this technique makes the modification of number of pulses per half cycle accessible.

3.1 varied pulse-width technique (VPW)

For a practical inverter, it is expected that a substantial amount of harmonics are generated due to the discontinuity of the output voltage. But for typical inverter operations, it is anticipated that the output voltage will be nearly a sinusoidal waveform. The VPW technique used in this work produces an adequate number of variant-width pulses (p) per half cycle. This approach lengthens the central pulse and shortens the exterior pulses, achieving a high performance based on an inverter output voltage close to the sinusoidal form and it has fewer amounts of harmonic contents. The variant pulse-widths to these pulses have been done somehow to ensure that the sum of the widths for the new variable pulses equals the width of the original pulse width to keep the same inverter operation.

Figure.1 shows that the original single-pulse angle is divided into number of pulses per half cycle (T_s). Starting from the middle pulse of width (σ_1), two groups of pulses are created; right group and left group of pulses. The widths of pulses per group are different, but the widths of pulses per boundary are similar.

The widths of the right-group pulses are: $\sigma_1, \sigma_2, \sigma_3, \sigma_4, \ldots, \sigma_R$

The widths of the left-group pulses are: $\sigma_1, \sigma_2, \sigma_3, \sigma_4, \ldots, \sigma_R$

The number of pulses per single group (R) is given by:

$$R = \frac{p+1}{2} \qquad (2)$$

The variant pulse-width for the pulses is obtained by increasing the pulse-width for some pulses and decreasing the same amount of width from other pulses in the way to maintain the same original pulse width for an inverter operation.

The subsections below determine the addition and subtraction values required for each pulse, to generate the variable-pulse widths that are shown in Fig.1.

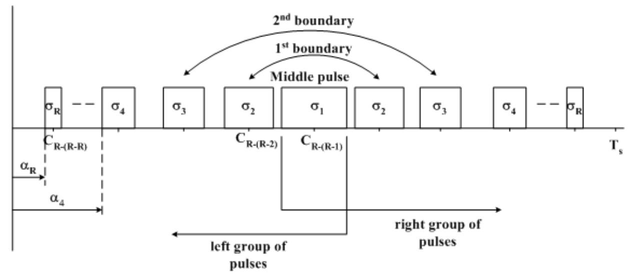

Fig.1 VPW technique

3.2 The width addition (A_k)

The width of the middle and boundary pulses is increased by (A_k) to become:

$$\sigma_k = \sigma + A_k , \qquad (k=1,2, 3, ..., R-1) \qquad (3)$$

A width addition equation for the middle and boundary pulses is developed and given as:

$$A_k = \sum_{k=1}^{R-1} \frac{1}{2^{k-1}} \frac{2\sigma}{a} \qquad (4)$$

, where: $a = \dfrac{\delta}{2p}$

In Equation (4), the summation is limited to (R-1), hence there is no addition to the last boundary of pulses. The addition of the middle pulse is compensated by all other pulses in the groups, but the adding of any boundary pulse is compensated only by the pulses of its own group.

3.3 The width subtraction (SUB)

There are two types of subtraction. The first subtraction is due to the addition to the middle-pulse which is covered by all pulses in the groups. It equals;

$$SUB_1 = \frac{1}{p-1} A_1 \qquad (5)$$

The second subtraction is due the addition to the boundary-pulse which is covered by the pulses in its own group only.

$$SUB_k = \sum_{k=2}^{R-1} \frac{1}{R-k} A_k \qquad (6)$$

Therefore, the additions for middle and boundary pulses by equation (4) are equilibrated by all pulses except the middle pulse. This is for maintaining the same width-value for the original pulse, thereafter keeping the same operation for the inverter but with less generation of harmonics.

3.4 Determination of the pulse center

For VPW technique, it is necessary to calculate the pulse-center of each pulse. This pulse-center is employed to calculate the gating angle of each pulse. Then the gating signals together with their corresponding pulse widths are composed to generate the pulse train required for inverter drive.

The widths of pulses per group are: $\sigma_1, \sigma_2, \sigma_3, \sigma_4 \ldots, \sigma_R$.
Their corresponding centers are: $C_{R-(R-1)}$, $C_{R-(R-2)}$, $C_{R-(R-3)}$ …, $C_{R-(R-R)}$, respectively.

The center of the middle-pulse is ($\frac{\pi}{2}$ *rad*) .

Assuming there is only two pulses are generated around the middle point, the center of the last pulse is ($\frac{1}{2}.\frac{\pi}{2}$ *rad*).

If there are (p-1)-pulses around the middle point, the center of the last pulse becomes:

$$C_{R-(R-R)} = \frac{1}{p-1}.\frac{\pi}{2} \quad rad \qquad (7)$$

The double-center value (D_{cen}) is defined as the twice value of the last pulse center and it is given by:

$$D_{cen} = 2 \times C_{R-(R-R)} \qquad (8)$$

The double-center value (D_{cen}) represents the difference between the centers of two consecutive pulses. Therefore, the center of the next pulse (C_{next}) is given by:

$$C_{next} = C_{prior} - D_{cen} \qquad (9)$$

3.5 Testing example

To verify that the algorithm proposed in section (3.1) for keeping the same original pulse width, after producing the variable pulse widths for middle and boundary pulses, an inverter operation is assumed at the original single pulse of: $\delta = 140^0$. The number of pulses per half cycle is assumed to be (7).

$$\sigma = \frac{\delta}{p} = \frac{140^0}{7} = 20^0$$

$$a = \frac{\delta}{2p} = \frac{140^0}{14} = 10^0$$

$$R = \frac{p+1}{2} = \frac{8}{2} = 4$$

<u>For middle-pulse:</u>

$$A_1 = \frac{1}{1} \times \frac{2 \times 20^0}{10} = 4^0 \text{ , so; } \sigma_1 = 20^0 + 4^0 = 24^0$$

<u>For 2nd boundary-pulse:</u>

$$A_3 = \frac{1}{2^2} \times \frac{2 \times 20^0}{10} = 1^0 \text{ , } SUB_2 = \frac{1}{4-2} \times 2^0 = 1^0 \text{, so; } \sigma_3 = 20^0 + 1^0 - 0.666^0 - 1^0 = 19.334^0$$

<u>For last boundary-pulse:</u>

$$A_4 = 0^0 \text{ , } SUB_3 = \frac{1}{4-3} \times 1^0 = 1^0 \text{, so; } \sigma_4 = 20^0 - 0.666^0 - 1^0 - 1^0 = 17.334^0$$

The new widths for middle and boundary pulses per half cycle are shown in Fig.2 and their sum is: $\sigma_1 + 2\sigma_2 + 2\sigma_3 + 2\sigma_4 = 24^0 + 42.668^0 + 38.668^0 + 34.668^0 = 140^0$, which equals the width of the original single pulse of: $\delta = 140^0$.

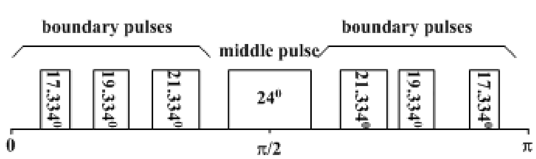

Fig.2 pulse widths for $\delta = 140^0$ and p= 7.

4. Results and discussions

The VPW technique is proposed to control the output voltage of a single phase inverter. The technique is improved the inverter operation so as to be nearly continuous and with minimum generation of harmonics. The paper has developed a software-mode instead of a hardware-mode to generate the gating signals of the inverter drive. This software-mode gives an opportunity to modify the number of pulses per half cycle without changing the width of the original pulse.

Various results are obtained for the new VPW technique. Figure.3 shows the harmonic profile for the VPM technique. The dominant harmonic is the third one. A comparison between the VPW technique and the conventional methods, for the third harmonic amplitude is shown in Fig.4. It is clear that the VPW technique gives the higher performance compared to that of conventional MPWM method, but it is not comparing to the SPWM technique. The VPW technique has a superior performance compared to the conventional SPWM method for the higher order of harmonics. In Figs. 5 and 6, it can be seen that for 9^{th} and 11^{th} harmonic order, the VPW technique has smaller harmonic amplitudes compared to the SPWM method.

The performance of the inverter operation is also evaluated in terms of the number of the pulses (p) per half cycle, since the number of pulses (p) per half cycle has an effect on the inverter performance. The third harmonic amplitude for VPW technique is shown in Fig.7. Results show that the harmonic amplitude is decreased as the number of pulses per half cycle is increases.

5. Conclusions

It is reasonable and intuitive to develop a control technique leading to minimum harmonic contents in the inverter output voltage towards optimum operation. The paper presented a new pulse-width technique to improve the inverter performance based on minimum harmonic contents in the output. A VPW software technique is developed to split the original pulse of an inverter operation into several pulses of varied- widths per half cycle. Also this technique made the modification of number of pulses per half cycle accessible. The harmonic amplitudes of an inverter output voltage using VPW technique is reduced compared to that of conventional methods, expressly for higher order harmonics.

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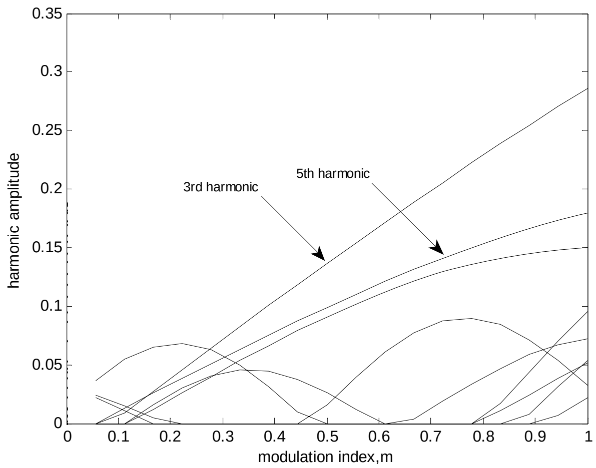

Fig.3 Harmonic profile for VPW, p=5

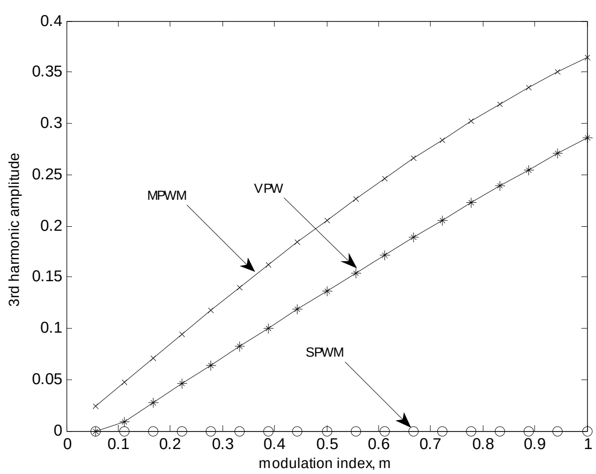

Fig.4 The 3rd harmonic amplitude for VPW technique and conventional techniques, p=5

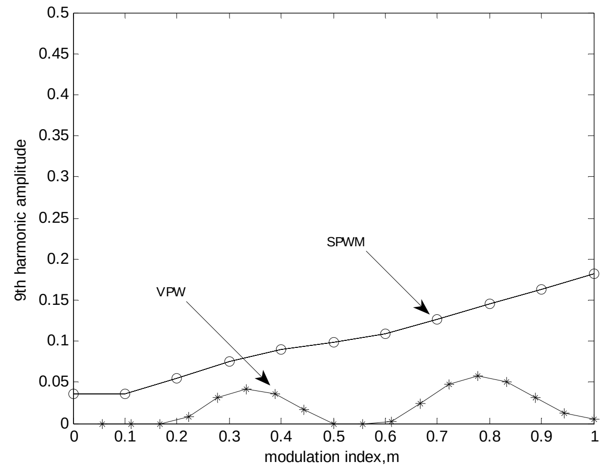

Fig.5 The 9^{th} harmonic amplitude for VPW and SPWM techniques, p=5

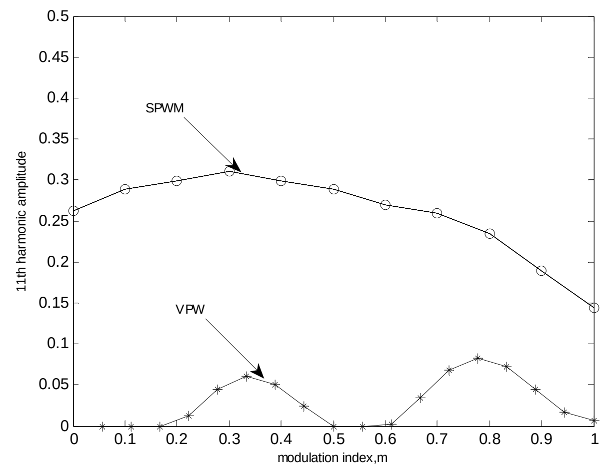

Fig.6 The 11^{th} harmonic amplitude for VPW and SPWM techniques, p=5

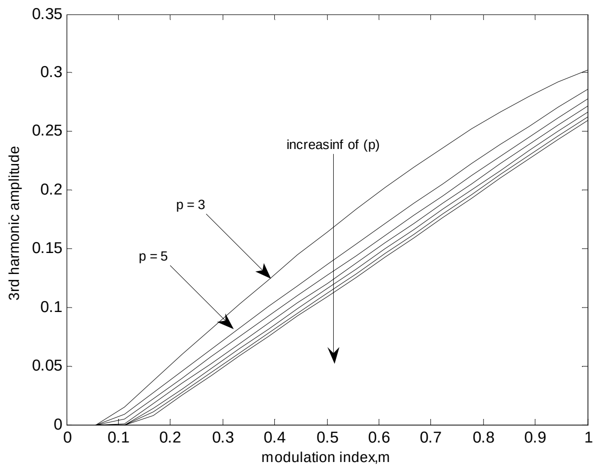

Fig.7 The third harmonic amplitudes for VPW, p=3, 5, …, 15